R78-1
JANUARY 1978

FINAL REPORT ON THE

ELECTROMECHANICAL FLIGHT CONTROL ACTUATOR

VOLUME 2

CONTRACT NAS 9-14952

Submitted to
NATIONAL AERONAUTICS and SPACE ADMINISTRATION
L.B. Johnson Space Center
Houston, Texas

Delco Electronics

General Motors Corporation
- Santa Barbara Operations
Santa Barbara, California

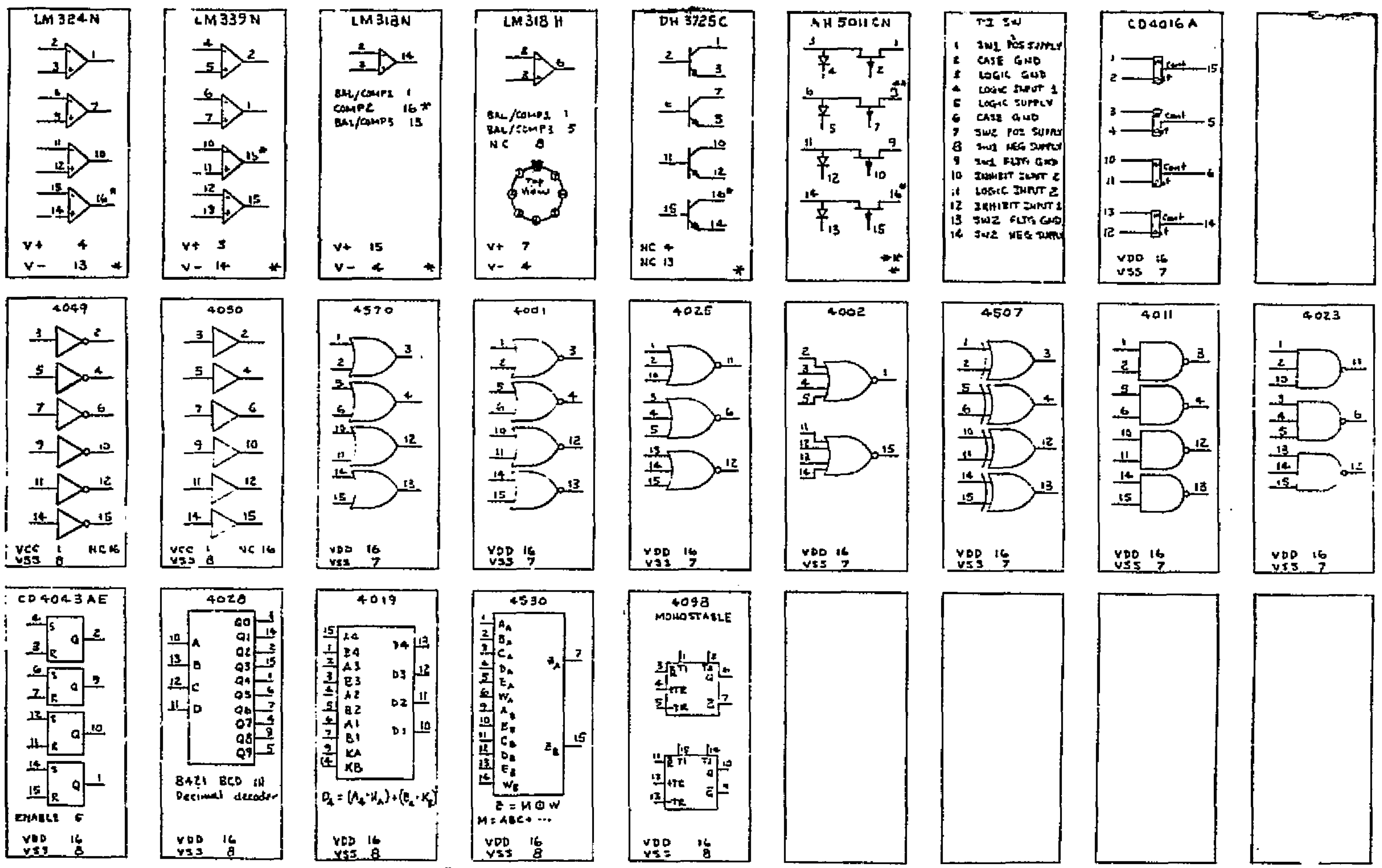
FOREWORD

This report is divided into three volumes. Volume 1 is the body of the report, Volume 2 contains Appendices A through I, and Volume 3 contains Appendices J through L.

APPENDIX A

SYSTEM SCHEMATICS

This appendix contains the schematic diagrams for both the four-channel electromechanical actuator and the single-channel power electronics breadboard.



NOTES:

* Cut VCC conductor
** Cut GND conductor

Unless otherwise noted:

1) All pins shown as Augat Board pins
2) Align pin 1 of DIP with Augat Board pin 1
3) All resistors 1/4 W, 5%
4) All diodes 1N4444
5) All electrolytic caps 35 V, 10%

SK 1220	DIPs	
SK 1221	Current Control	B
SK 1222	Pwr Sw Control	C
SK 1223	Servo Amp.	D
SK 1224	Rotor Pos Sensor	E
SK 1225	Mode Control	G
SK 1226	Velocity Correction	G
SK 1227	Power Control	
SK 1228	Power Switches	
SK 1229	±6V Pwr Supplies	
SK 1230	Brake Control	
SK 1231	Power Interconnect	
SK 1232	Power Sw Wiring	
SK 1233	Cabling	
SK 1234	Front Panel Wiring-Logic	
SK 1235	Power Control Panel	
SK 1236	Logic Control Panel	
SK 1237	Rack Sw and Arrangement	
SK 1238	Test Buffers	

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E-M ACTUATOR DIPs, ETC.
NASA

H Hansen 3-26-76

13160 SK001220

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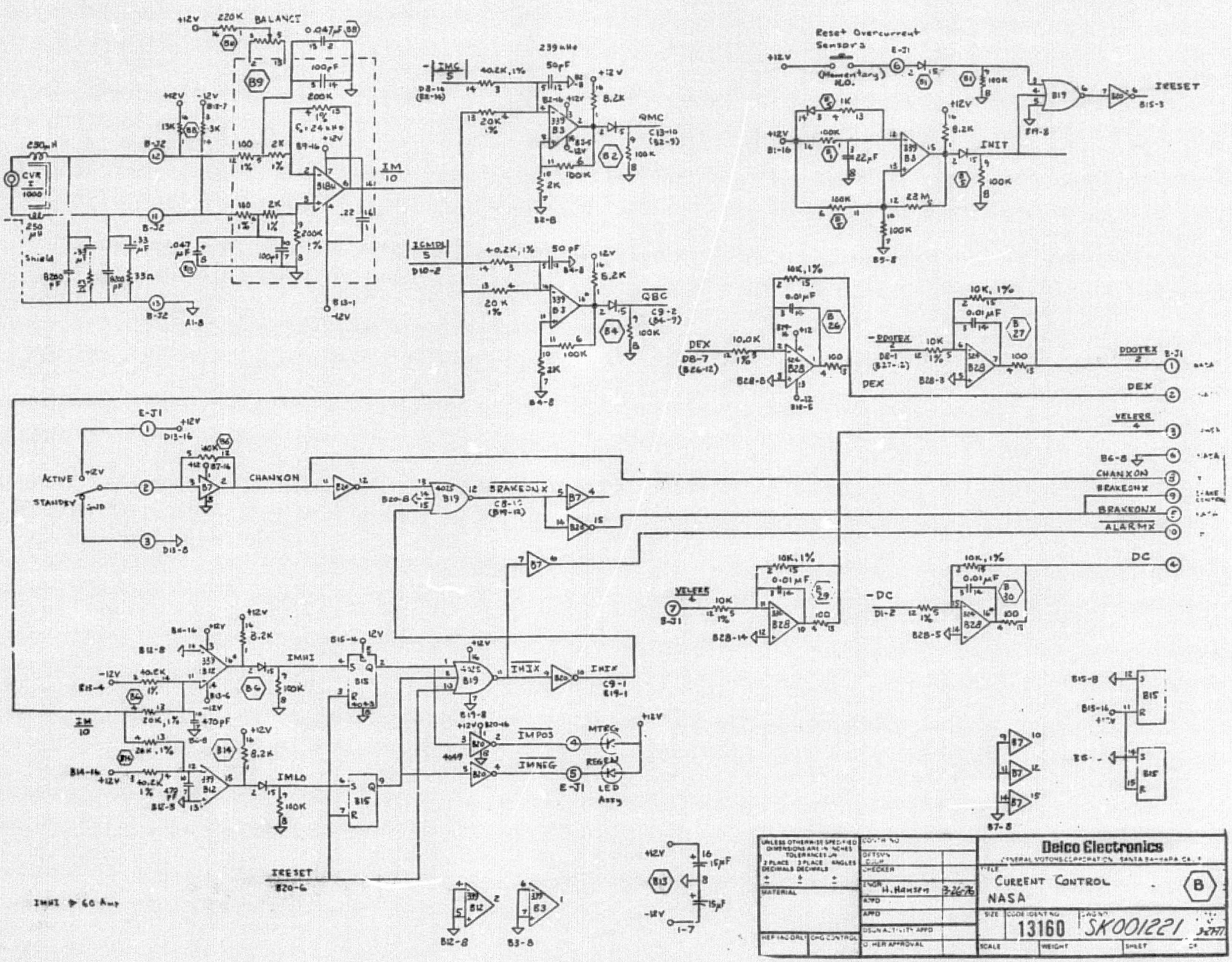
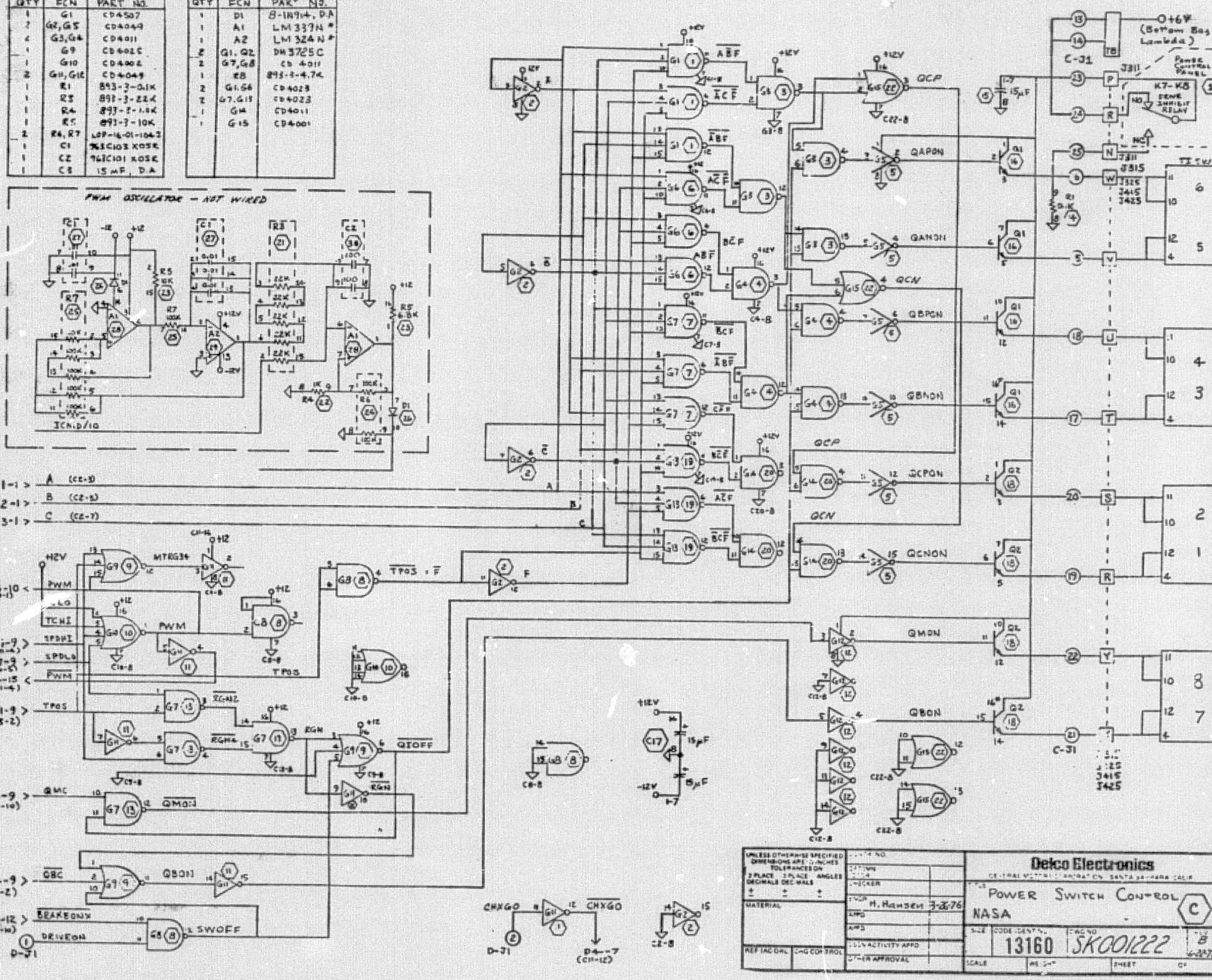


Delco Electronics
GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF.
CURRENT CONTROL
NASA
B
H. Hansen 3-26-76
13160
SK001221
IRESET
BALANCE
Reset Overcurrent Sensors
(Momentary) N.O.
ACTIVE
STANDBY
CHANXON
BRAKEONX
ALARMX
DDOTEX
DEX
VELERR
DC
IMPOS
IMNEG
MTRG
REGEN
LED Assy
IMHI
IMLO
INIT
QMC
QBC
IMHI ≥ 60 Amp

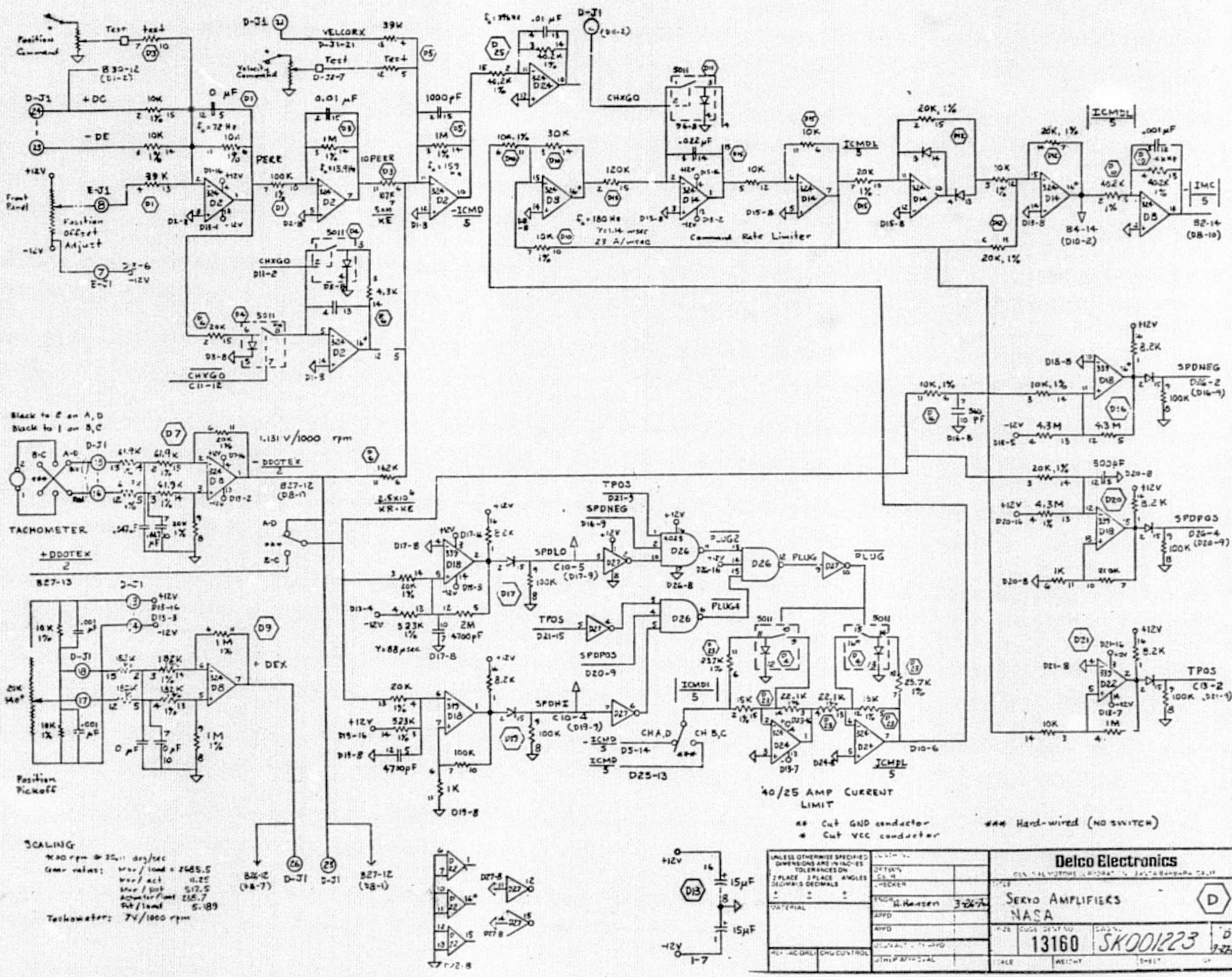
QTY	FCN	PART NO.
1	G1	CD4507
2	G2, G5	CD4049
4	G3, G4	CD4011
1	G9	CD4025
1	G10	CD4002
2	G11, G12	CD4049
1	R1	893-3-0.1K
1	R3	893-3-22K
1	R4	893-3-1.0K
1	R5	893-3-10K
2	R6, R7	L0P-16-01-1043
1	C1	963C103 X05K
1	C2	963C101 X05K
1	C3	15 mF, D.A

QTY	FCN	PART NO.
1	D1	8-1N914, D.A
1	A1	LM 339N *
1	A2	LM 324N *
2	Q1, Q2	DH 3725C
2	G7, G8	CD 4011
1	R8	893-3-4.7K
2	G1, G6	CD4023
2	G7, G13	CD4023
1	G14	CD4011
1	G15	CD4001

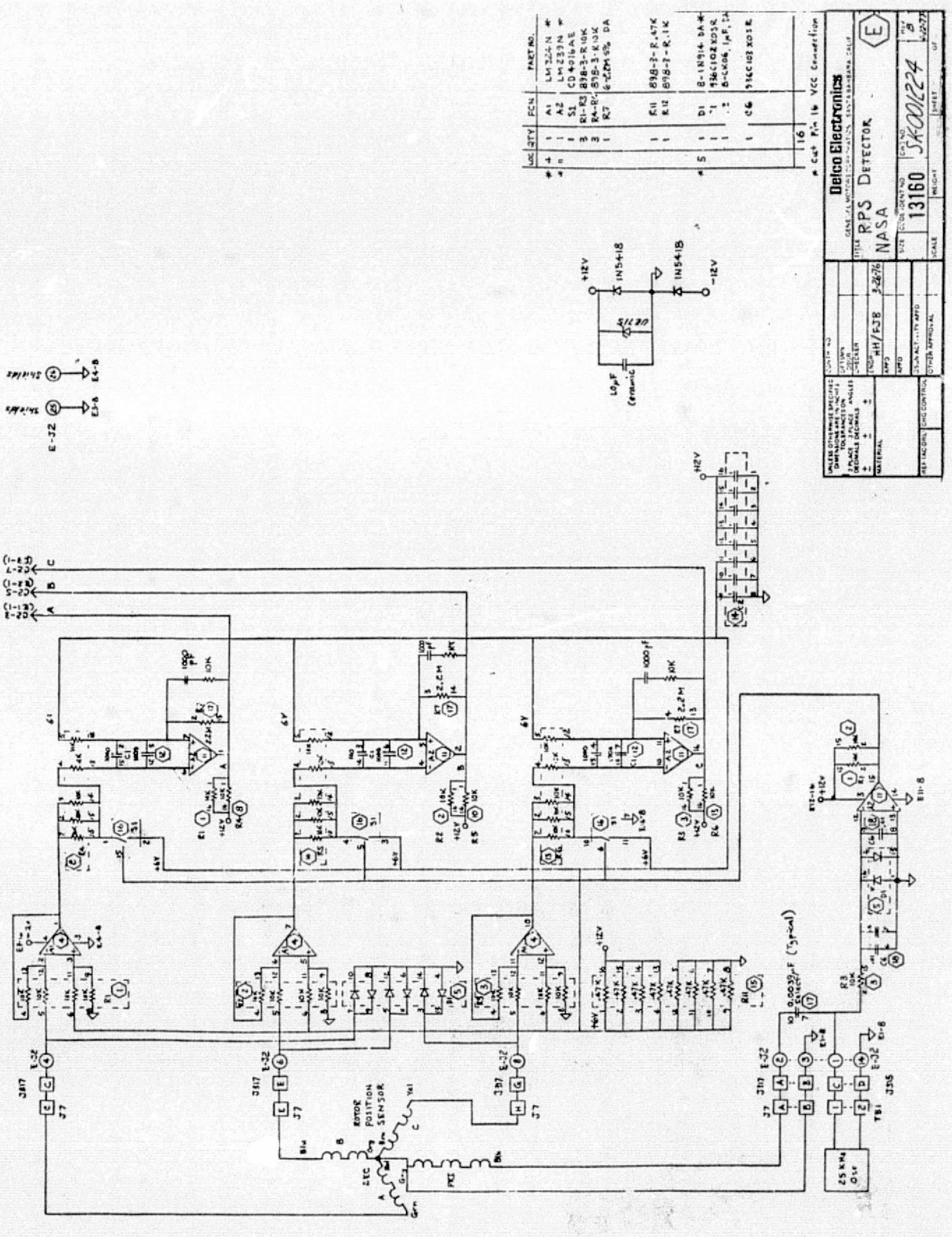


UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS 3 PLACE DECIMALS ANGLES ± ± ±	CONTR NO.	**Delco Electronics** GENERAL MOTORS CORPORATION SANTA BARBARA CALIF
MATERIAL	DRAWN / CHECKER / ENGR H. Hansen 3-26-76 / APPD / APPD	TITLE POWER SWITCH CONTROL NASA (C)
REF IAC DRL / CHG CONTROL	DSGN ACTIVITY APPD / OTHER APPROVAL	SIZE / CODE IDENT NO. 13160 / DWG NO. SK001222 / REV B 6-22-77
		SCALE / WEIGHT / SHEET OF

ORIGINAL PAGE IS OF POOR QUALITY



DELCO ELECTRONICS DIVISION • SANTA BARBARA OPERATIONS • GENERAL MOTORS CORPORATION



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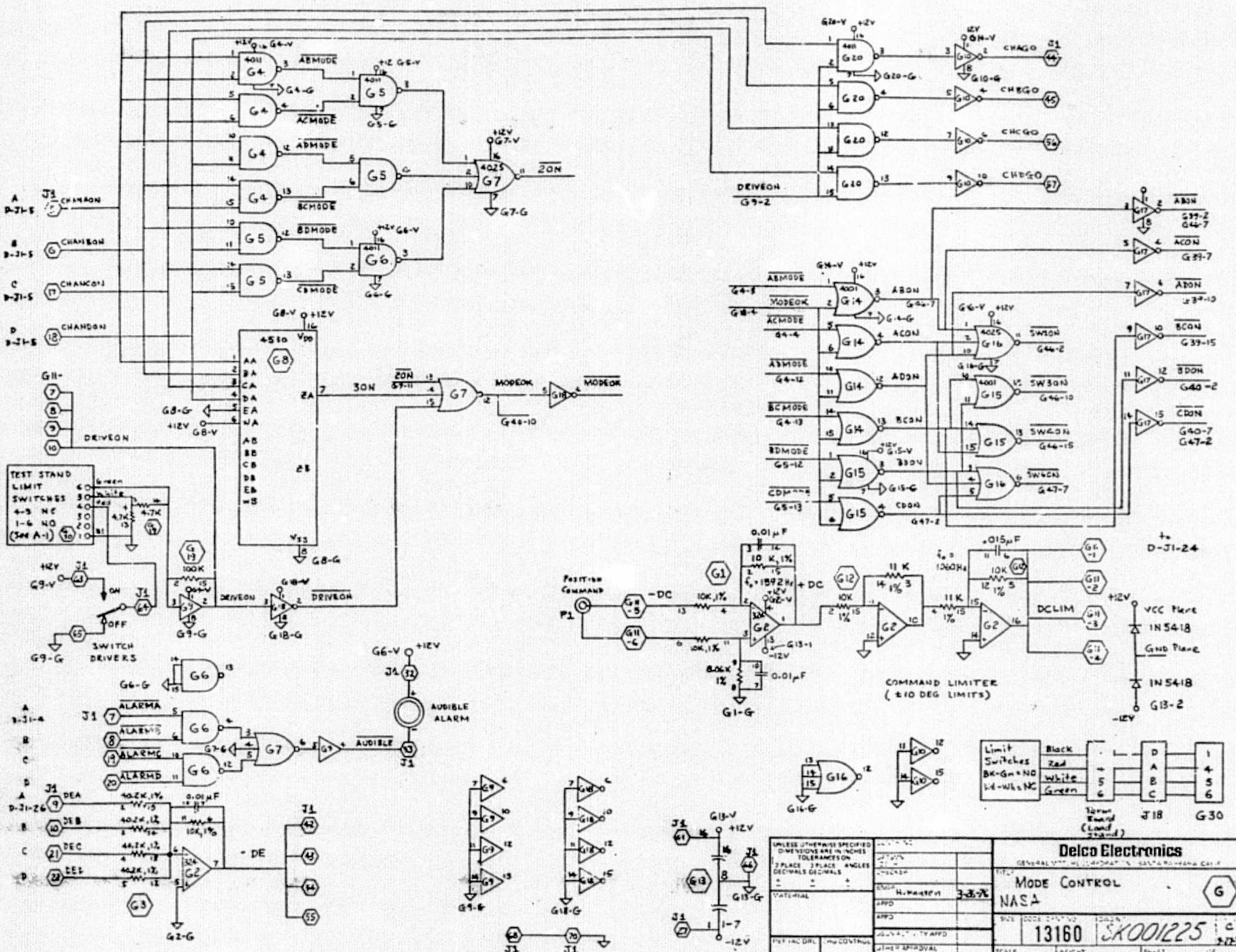
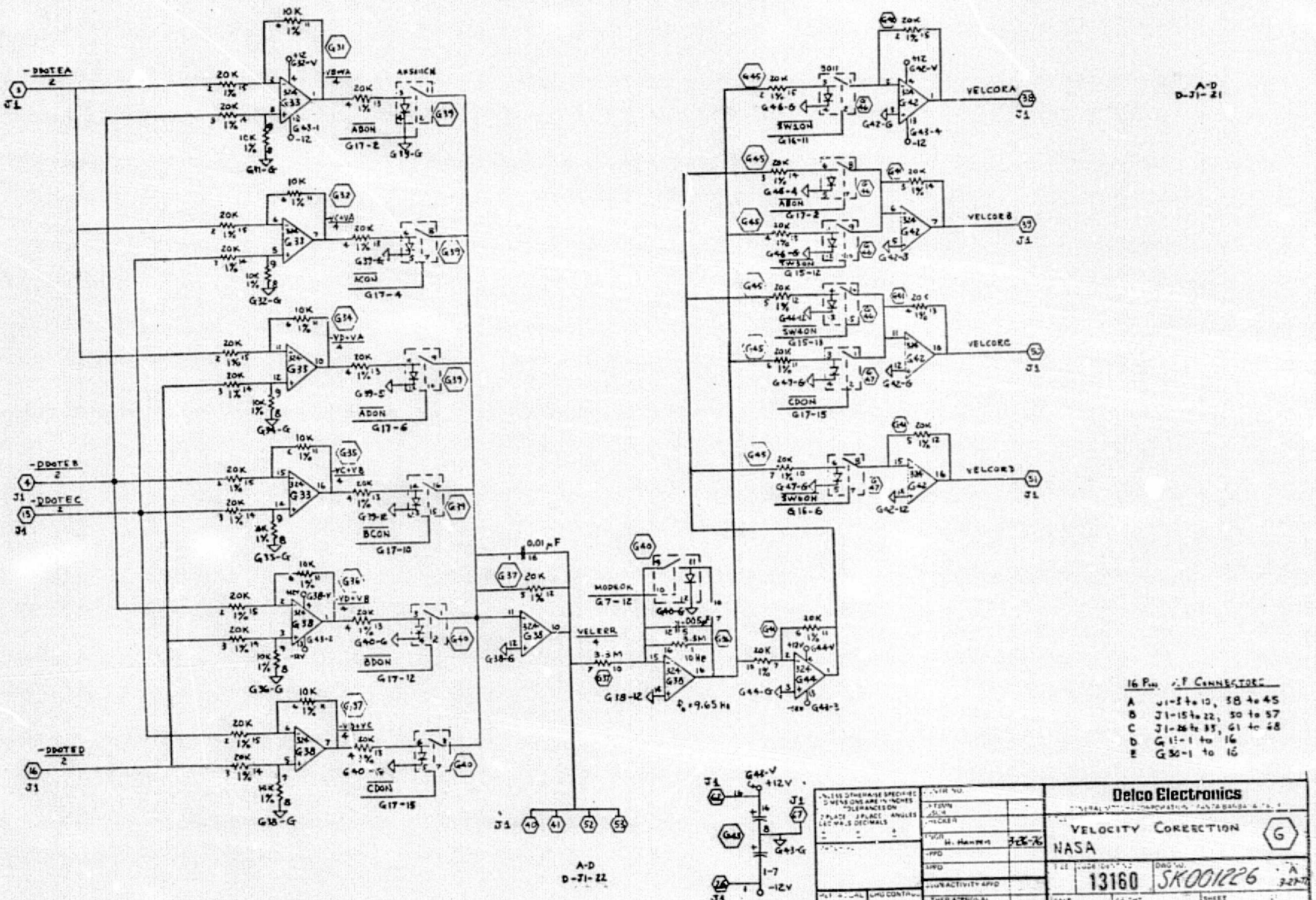
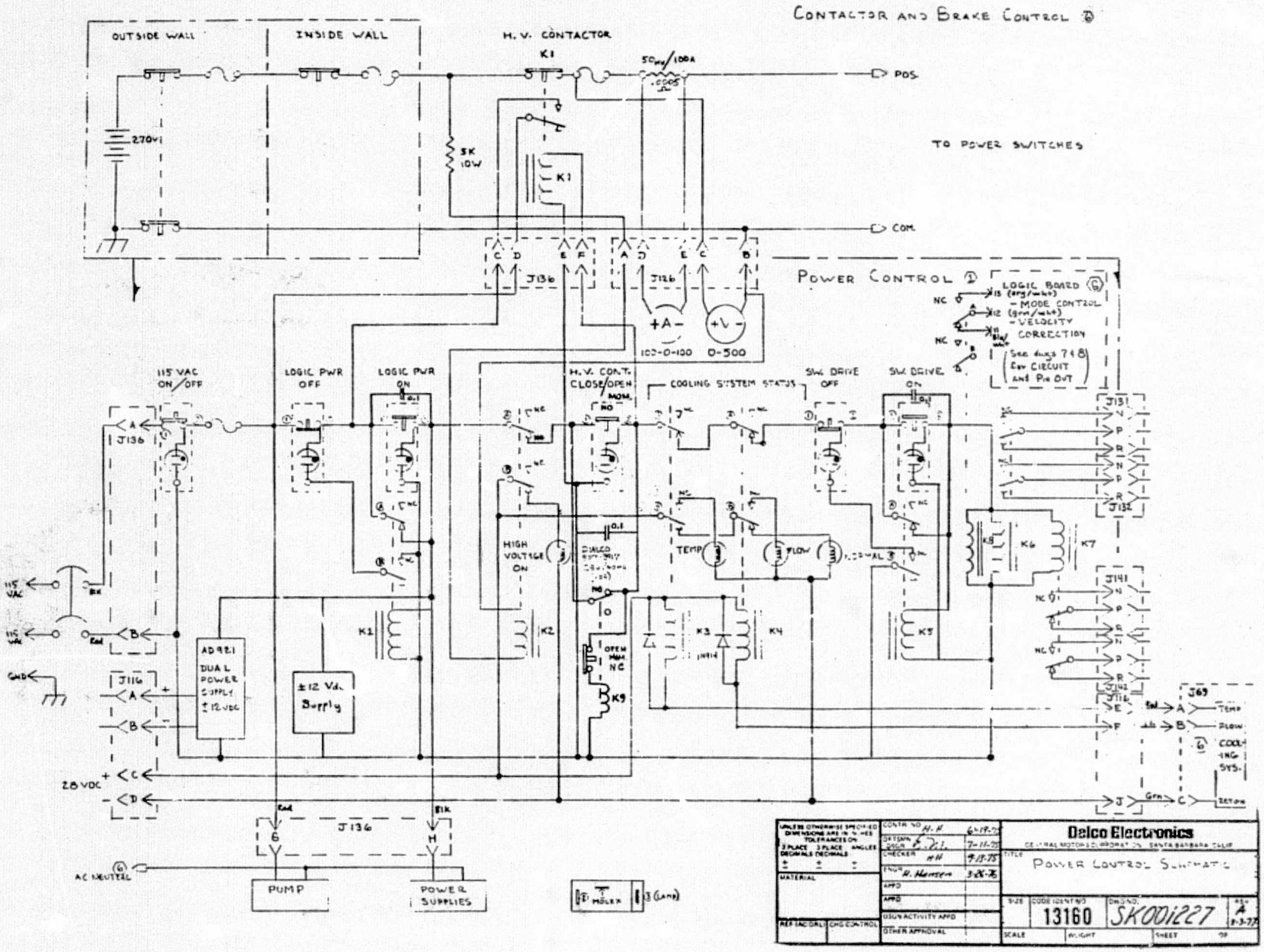


TEST STAND LIMIT SWITCHES 4-5 NC 1-6 NO (See A-1)
SWITCH DRIVERS
AUDIBLE ALARM
POSITION COMMAND
COMMAND LIMITER (±10 DEG LIMITS)
Limit Switches BK-Gn = NO Wt-Wh = NC
Delco Electronics
MODE CONTROL
NASA
13160
SK001225


-DDOTEA/2
-DDOTEB/2
-DDOTEC/2
-DDOTED/2
VELERR/4
MODEOK
G7-12
VELCORA
VELCORB
VELCORC
VELCORD
A-D D-J1-21
A-D D-J1-22
Delco Electronics
VELOCITY CORRECTION
NASA
13160
SK001226
H. Hansen



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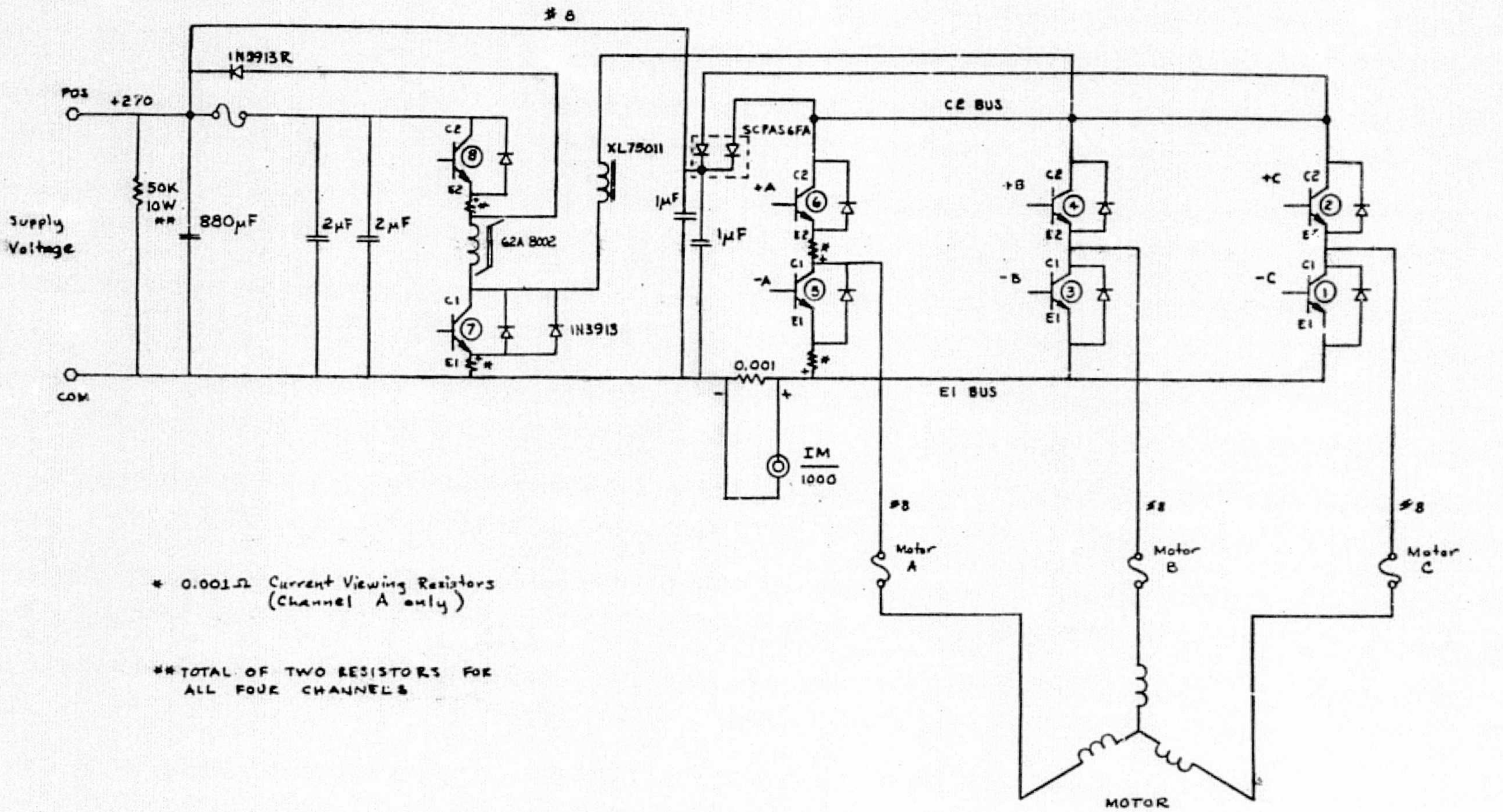
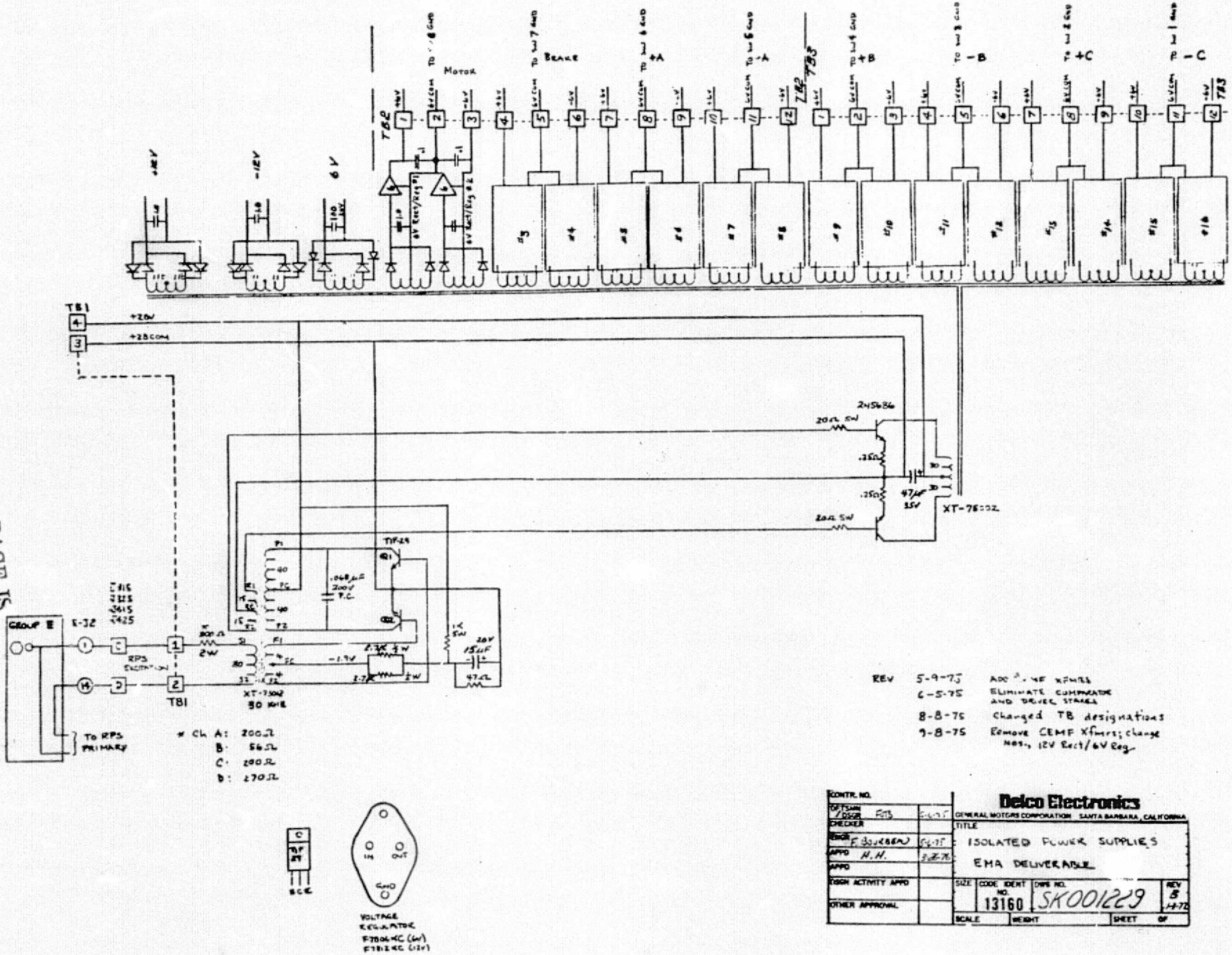


UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±	CONTR NO / DFTSMN / CHECKER / ENGR H. Hansen 3-26-76 / APPD / APPD / DSGN ACTIVITY APPD / OTHER APPROVAL	**Delco Electronics** GENERAL MOTORS CORPORATION SANTA BARBARA CALIF
MATERIAL		TITLE POWER SWITCH DRAWER NASA
REF (AC-DRL) / CHG CONTROL		SIZE D · CODE IDENT NO 13160 · DWG NO SK001228 · REV 11-3-77 · SCALE · WEIGHT · SHEET OF

R78-1



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REV	
5-9-75	Add 4 - 4E XFMRS
6-5-75	ELIMINATE COMPARATOR AND DRIVER STAGES
8-8-75	Changed TB designations
9-8-75	Remove CEMF Xfmrs; change Nos., 12V Rect/6V Reg.

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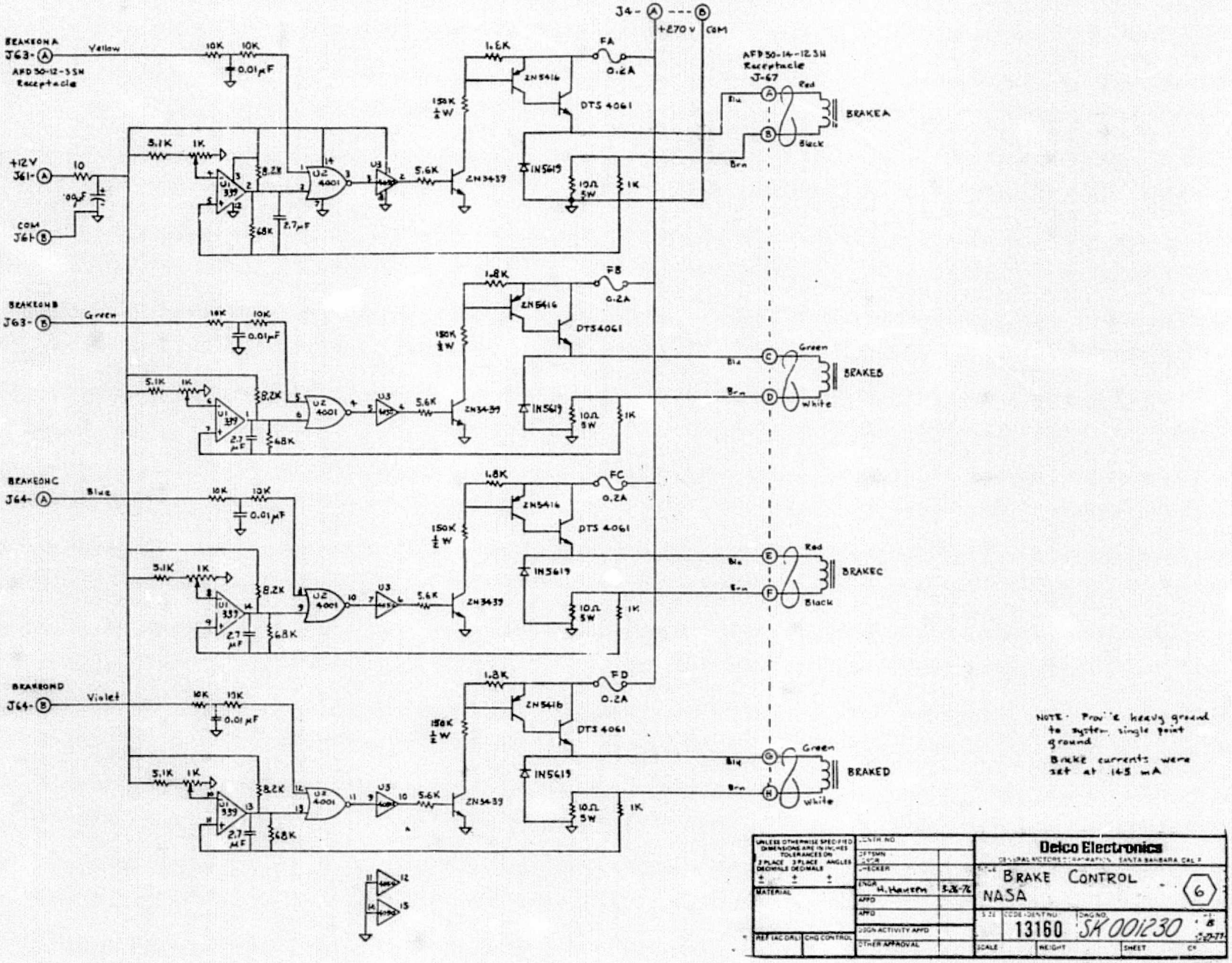
GENERAL MOTORS CORPORATION SANTA BARBARA, CALIFORNIA

CONTR. NO.		
DFTSMN / DSGR	FJS	
CHECKER		
ENGR	F. BOURGEN	
APPD	H.H.	
APPD		
DSGN ACTIVITY APPD		
OTHER APPROVAL		

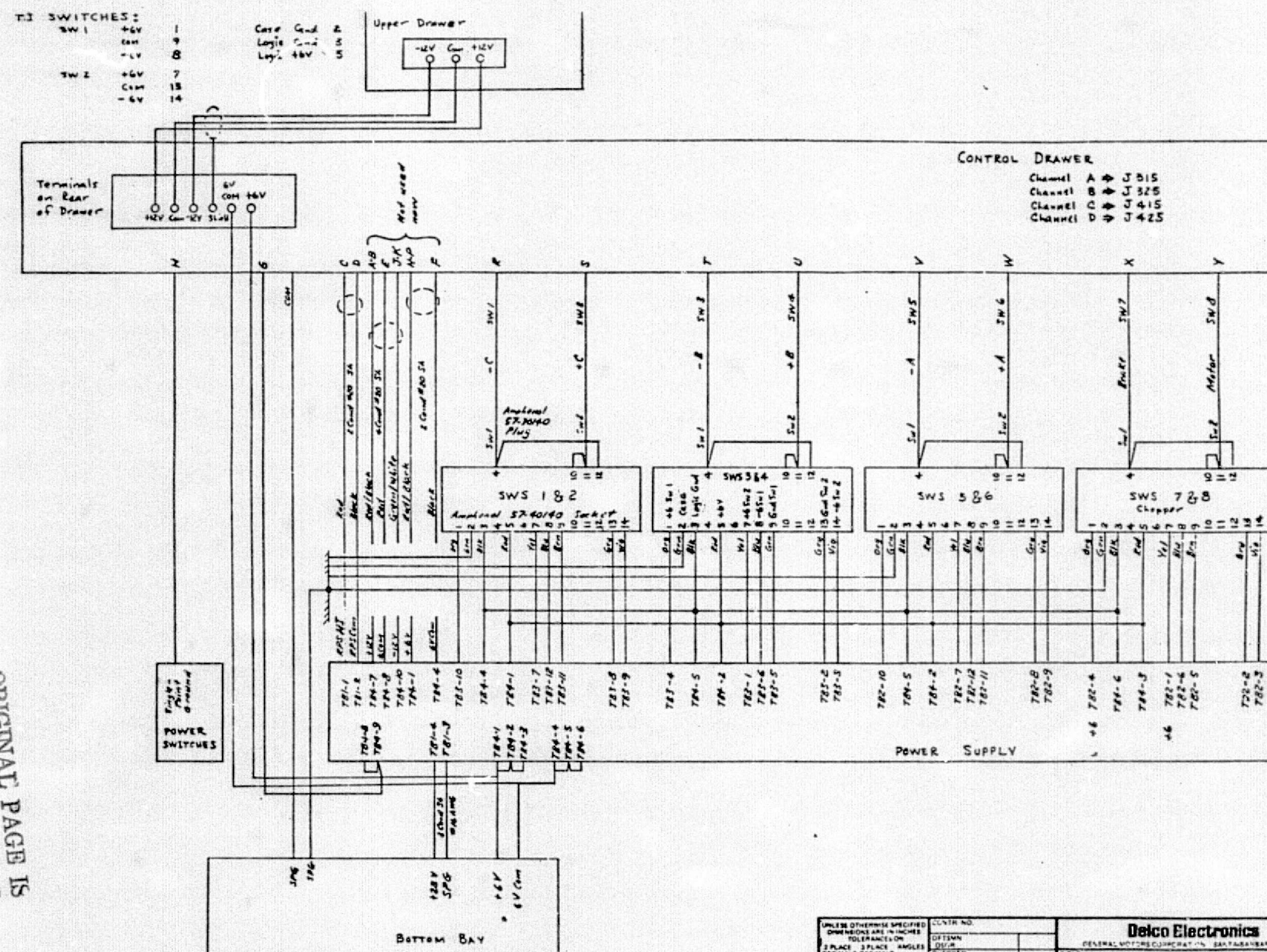
TITLE: ISOLATED POWER SUPPLIES EMA DELIVERABLE

SIZE	CODE IDENT NO.	DWG NO.	REV
	13160	SK001229	B

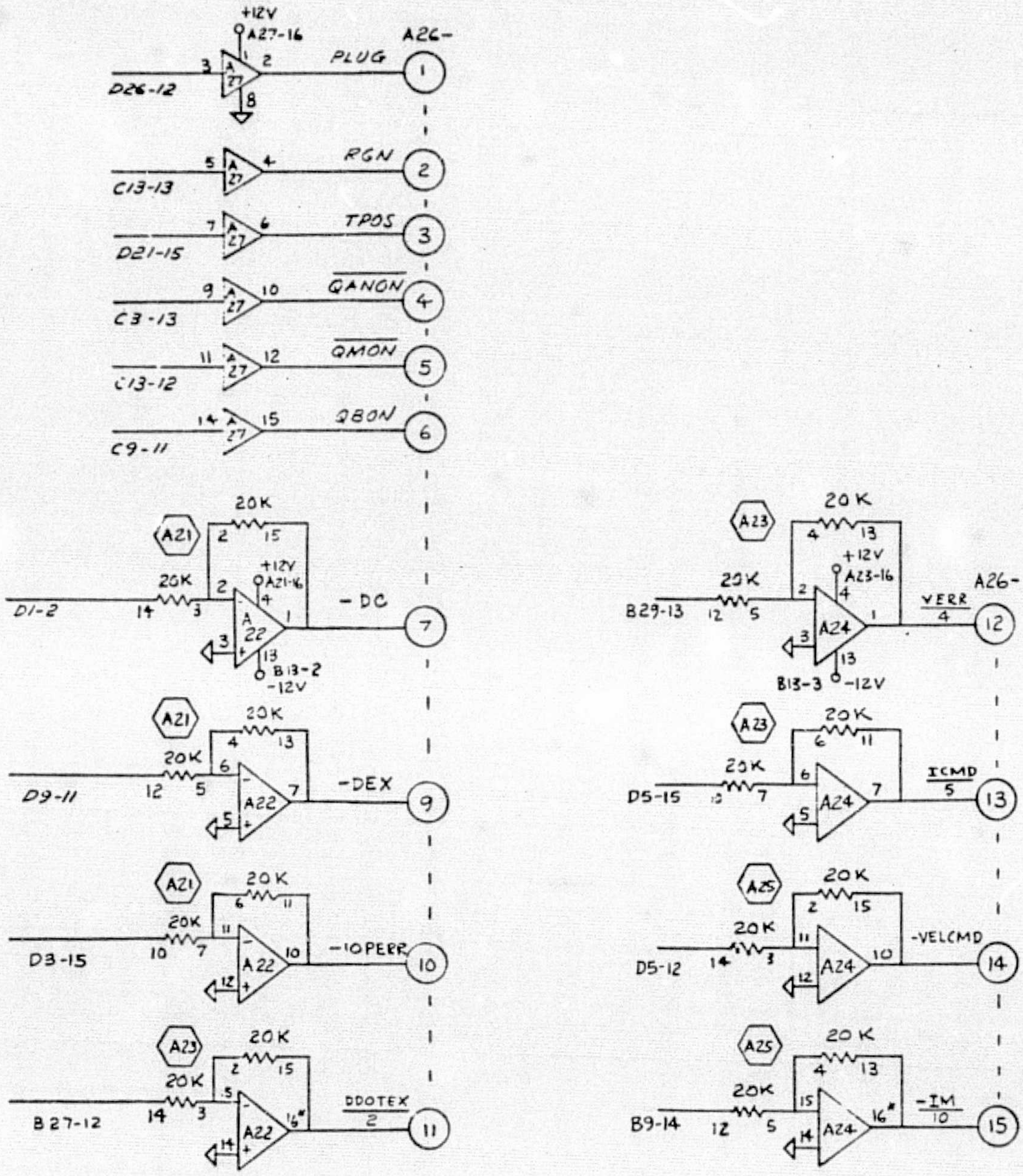
SCALE | WEIGHT | SHEET | OF



J4- A --- B
+270 V
COM
BRAKEONA
J63- A
Yellow
AFD 30-12-3 SN Receptacle
AFD 30-14-12 SN Receptacle
J-67
BRAKEA
BRAKEONB
J63- B
Green
BRAKEB
BRAKEONC
J64- A
Blue
BRAKEC
BRAKEOND
J64- B
Violet
BRAKED
+12V
J61- A
COM
J61- B
2N5416
DTS 4061
2N3439
IN5619
0.2A
NOTE · Provide heavy ground to system single point ground
Brake currents were set at .165 mA
Delco Electronics
BRAKE CONTROL
NASA
H. Hansen
13160
SK 001230



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±	CONTR NO.	Delco Electronics GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF.	
MATERIAL	DFTSMN	TITLE Power Switch Control NASA	
	CHECKER		
	ENGR H. Hansen 3-3-76		
	APPD	SIZE	CODE IDENT NO. 13160
	APPD	DWG NO. SK001232	REV B
REF (AC DRL) / CHG CONTROL	DSGN ACTIVITY APPD	SCALE	WEIGHT
	OTHER APPROVAL	SHEET	OF



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON: 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±	DRAWN / CHECKED / H Hansen 8-5-77 / APPD / APPD / DSGN ACTIVITY APPD / OTHER APPROVAL	**Delco Electronics** GENERAL MOTORS CORPORATION SANTA BARBARA CALIF.
MATERIAL		TITLE: TEST BUFFERS (A)
REF. 1AC DRL / CHG CONTROL		SIZE B / CODE IDENT NO. 13160 / DWG NO. SK001233 / 1-3-77
		SCALE / WEIGHT / SHEET

R78-1

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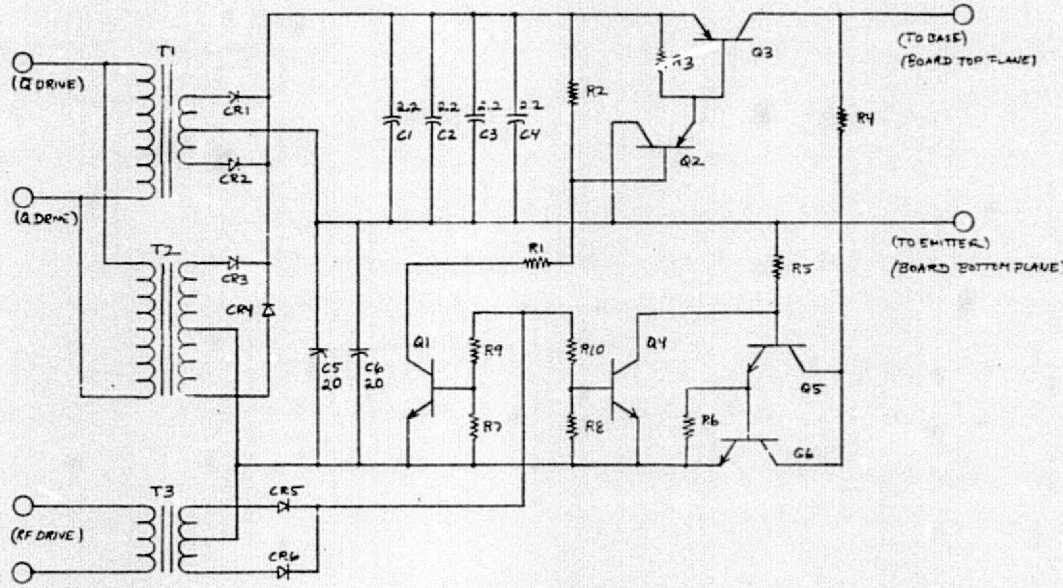


PARTS LIST

C1-C4	2.2 µF/30VDC, K12A225KSC, CRC
C5, C6	20 µF/30VDC, K12A206KSC, CRC
CR1, CR2	1N5831, SCHOTTKY RECT, MOTOROLA, 10-32 STUD
CR3, CR4	1N6079, SUPER FAST REC. SI RECT., SEMTECH
Q1, Q4, Q5	2N5320, NPN, TO-5, RCA
Q2	2N5333, PNP, TO-5, TI
Q3	2N6377, PNP, TO-3, MOTOROLA
Q6	2N6274, NPN, TO-3, MOTOROLA
R1, R5	330, 1W, 5%, CARBON RESISTOR
R2, R3, R6	75, 1/2W, 5%, " "
R4	TBD RWR-74N, ESN-5, DALE
R7, R8	200, 1/4W, 5%, CARBON RESISTOR
R9, R10	1K, 1/2W, 5%, " "

NOTES

A. T1 IS DELCO DESIGN XT77005
B. T2 IS DELCO DESIGN XT77006
C. T3 IS DELCO DESIGN XT77007
D. CR1, CR2 MOUNTED WITH AHAM 436-1.25 HEATSINK
E. Q2 MOUNTED WITH AHAM HS102-2-B-318 HEATSINK
F. Q3 MOUNTED WITH AHAM 436-1.25-TO3 AND AHAM 425 HEATSINKS
G. Q6 MOUNTED WITH AHAM 425 HEATSINK AND WAKEFIELD 177-3-62 BeO INSULATOR
H. USE HEATSINK THERMAL COMPOUND IN MOUNTING CR1, CR2, Q2, Q3, AND Q6

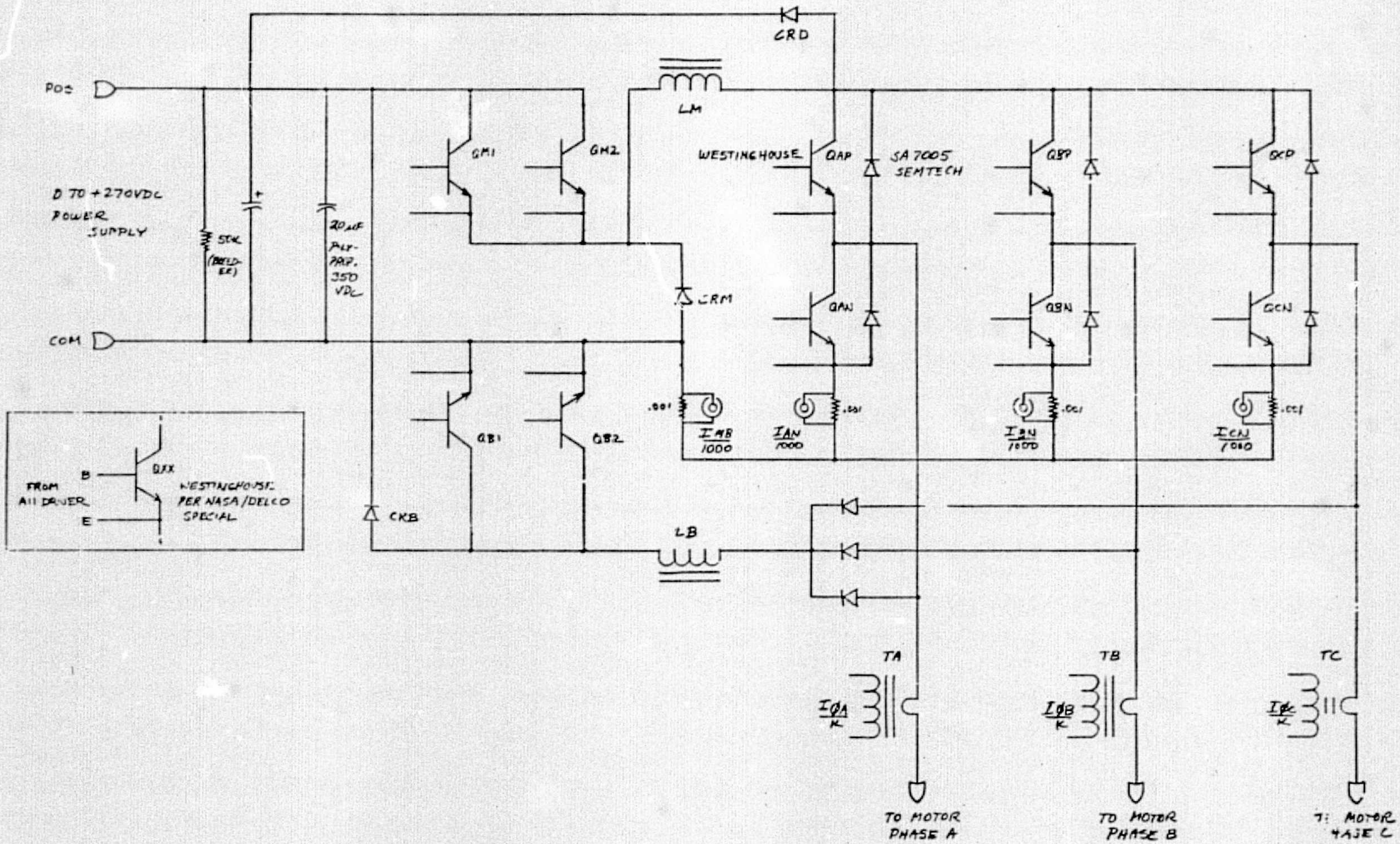
CONSTRUCT 12 BOARDS
PCB DESIGNATION - A11DRIVER

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON:
2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±
MATERIAL
REF (AC DRL) CHG CONTROL
CONTR NO
DFTSMN DSGR G.H.R. 8/6/77
CHECKER
ENGR G.H. Ko[illegible] 8/6/77
APPD
APPD
DSGN ACTIVITY APPD
OTHER APPROVAL

Delco Electronics
GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF.

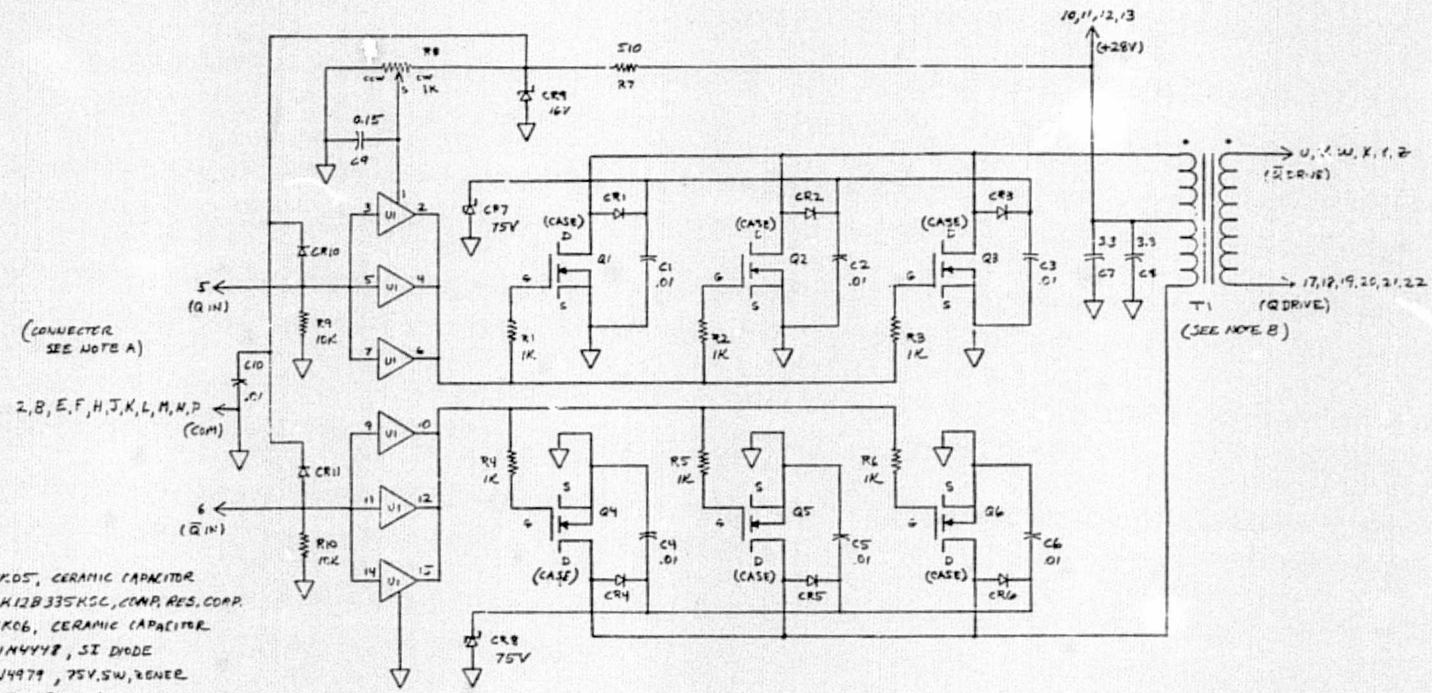
TITLE NASA HIGH POWER BASE DRIVER - DRIVER OUTPUT (10 REQUIRED) SCHEMATIC DIAGRAM

SIZE C CODE IDENT NO 13160 DWG NO SK001239 REV
SCALE WEIGHT SHEET 1 OF 1



REV A DELETE FUSE, CHANGE FILTER CAP. 9/21/77
PRELIMINARY ONLY G.K.B. 8/6/77

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±	CONTR NO.	**Delco Electronics** GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF
	DFTSMN G.K.B. 8/6/77	TITLE NASA HIGH POWER MOTOR DRIVER SCHEMATIC DIAGRAM
MATERIAL	CHECKER	
	ENGR C.H. Darrell	
	APPD	
	APPD	SIZE C · CODE IDENT NO. 13160 · DWG NO. SK001240 · REV A
	DSGN ACTIVITY APPD	
NEXT ASSY · USED ON · CHG CONTROL	OTHER APPROVAL	SCALE · WEIGHT · SHEET 1 OF 1



PARTS LIST

C1-C6, C10	0.01μF, CK05, CERAMIC CAPACITOR
C7, C8	3.3μF/50V K12B335KSC, COMP. RES. CORP.
C9	0.15μF, CK06, CERAMIC CAPACITOR
CR1-CR6, CR10, CR11	1N4448, SI DIODE
CR7, CR8	1N4979, 75V, 5W, ZENER
CR9	1N5568B, 16V, 1W, ZENER
R1-R6	1K, 1/4W, 5%, CARBON RESISTOR
R7	510, 1W, 5%. " "
R8	1K, 20T, TRIMPOT, BOURNES, 3252W-1-102
R9, R10	10K, 1/4W, 5%, CARBON RESISTOR
Q1-Q6	2N6658, VMOSFET, SILICONIX, TO-3
U1	CD4050BE, CMOS, RCA

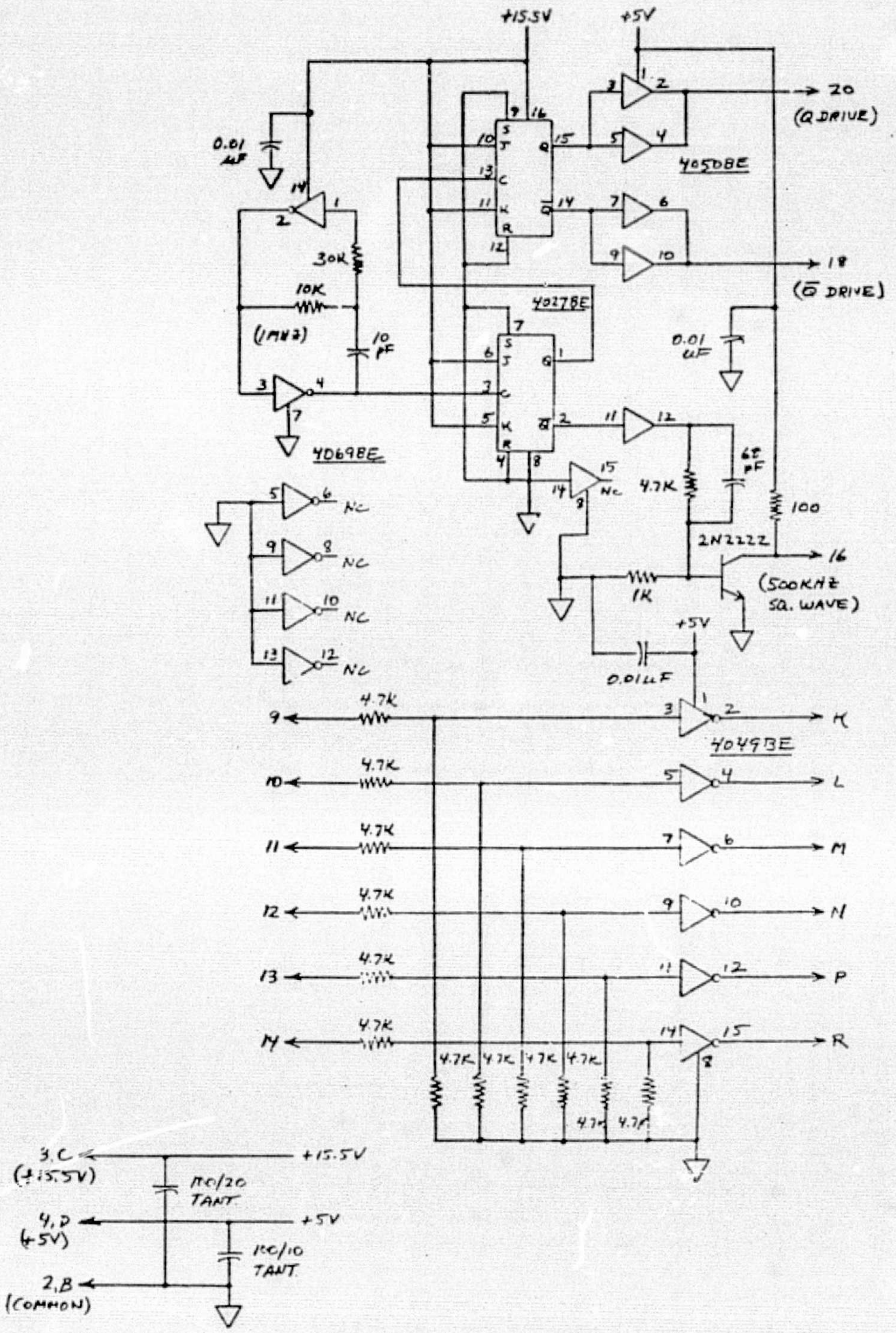
NOTES

A. MATING CONNECTOR, ELCO 00-6007-044-450-013
B. T1 IS DELCO DESIGN XT77008
C. U1 - PINS 13, 16, NO CONNECTION ALLOWED
D. Q1 - Q6 MOUNTED ON AHAM 436-1.25-TO3 HEATSINK WITH WAKEFIELD 177-3-62 BeO INSULATOR AND THERMAL COMPOUND

CONSTRUCT 6 BOARDS

PCB DESIGNATION - A10 BDPS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±	CONTR NO		**Delco Electronics** GENERAL MOTORS CORPORATION SANTA BARBARA CALIF
	DFTSMN G.H.B.	2/4/77	TITLE NASA HIGH POWER BASE DRIVER — POWER SUPPLY (3 REQUIRED) SCHEMATIC DIAGRAM
	CHECKER		
MATERIAL	W.H. Emmett	2/4/77	
	APPD		SIZE C — CODE IDENT NO 13160 — DWG NO. SK 001241 — REV
	APPD		
NEXT ASSY / USED ON — CHG CONTROL	DSGN ACTIVITY APPD		
	OTHER APPROVAL		SCALE — WEIGHT — SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS 3 PLACE DECIMALS ANGLES ± ± ±

MATERIAL

REF (AC DRL) CHG CONTROL

CONTR. NO.

DRAWN DESIGN A.H.E. 12/18/77

CHECKER

ENGR. [illegible] 2/10/77

APPD

APPD

DSGN ACTIVITY APPD

OTHER APPROVAL

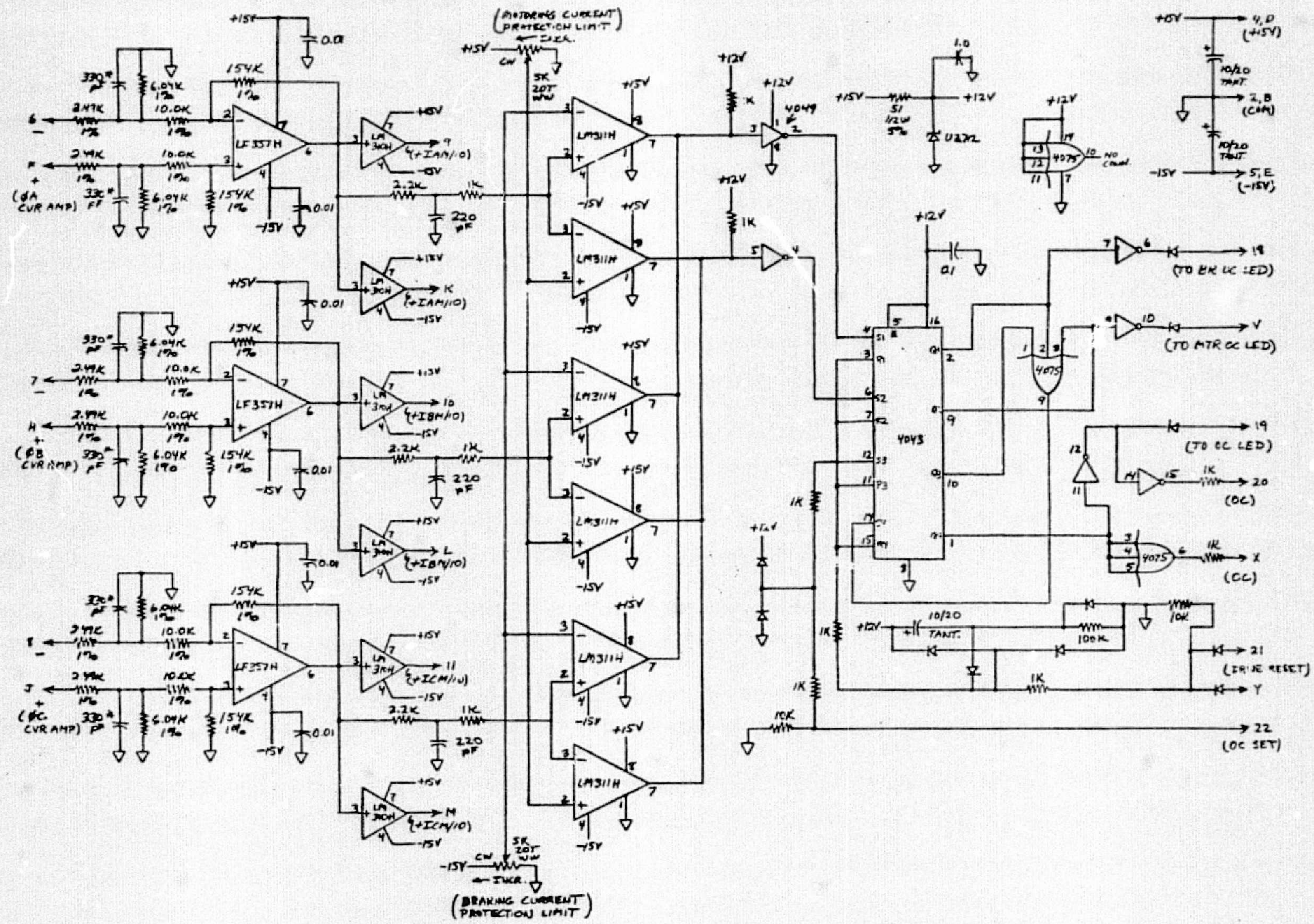
Delco Electronics

GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF

TITLE NASA QAP-QCW CONT INTERFACE, Q-$\bar{Q}$ DRIVE A11

SIZE C CODE IDENT NO 13160 DWG NO. SK 002076 REV

SCALE WEIGHT SHEET 1 OF 1



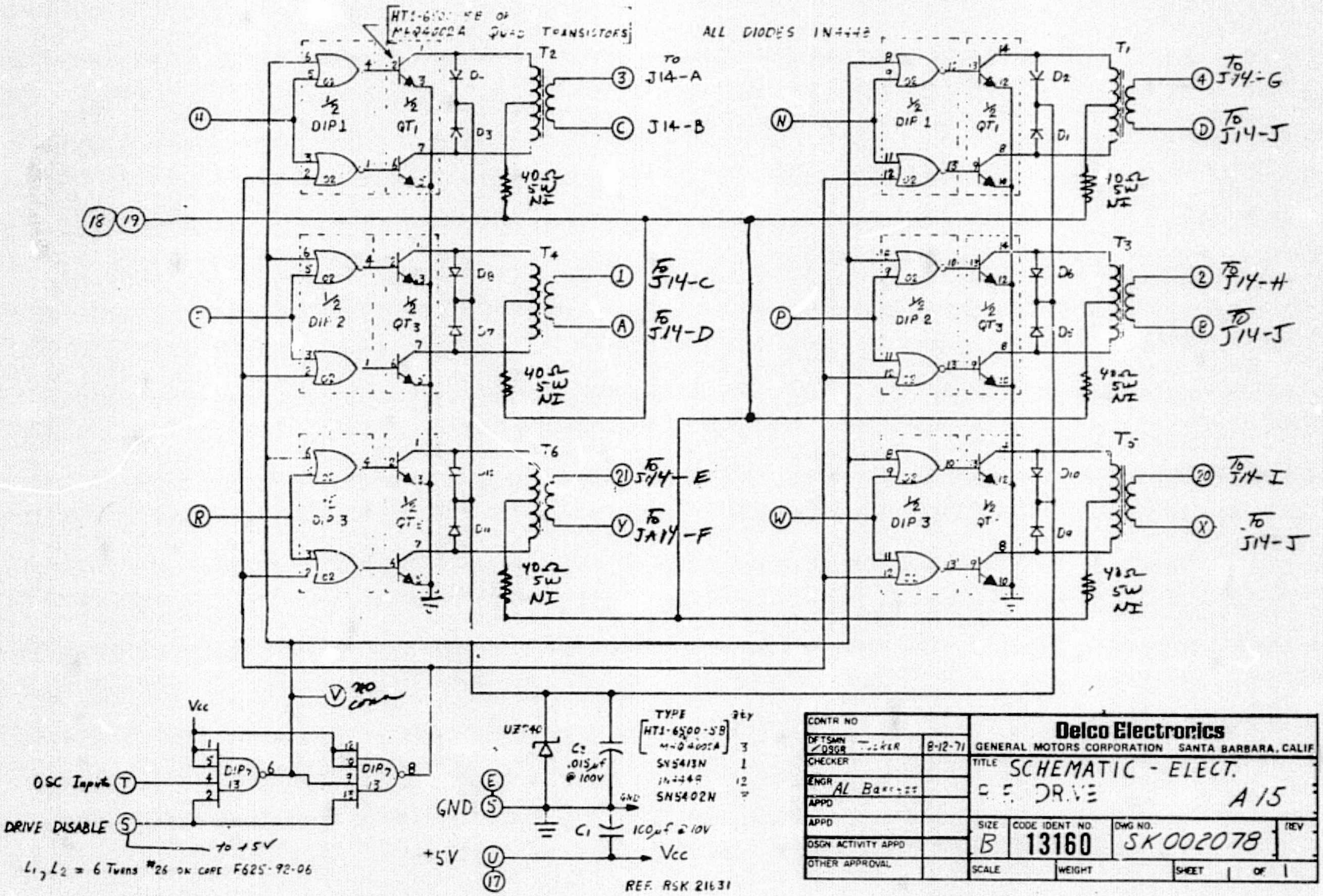
NOTE I: TWISTED PAIRS TO 6,F ; 7,H ; 8,J
NOTE H: CAPS. CK05 OR CK06 (EAN)
NOTE G: CD4XXX BE PREFERRED FOR 4000 SERIES CMOS
NOTE F: OR LM OR LF TYPES SUBS. L_2__ OR L_1__
NOTE E: * CAPS MATCHED ± 1%
NOTE D: ALL CAPACITOR VALUES IN MICROFARADS (EAN)
NOTE C: ALL 1% RESISTORS RN55D OR RN60D
NOTE B: ALL RESISTORS 1/4W 5% EXCEPT AS NOTED (EAN)
NOTE A: ALL DIODES 1N4148 OR 1N4448

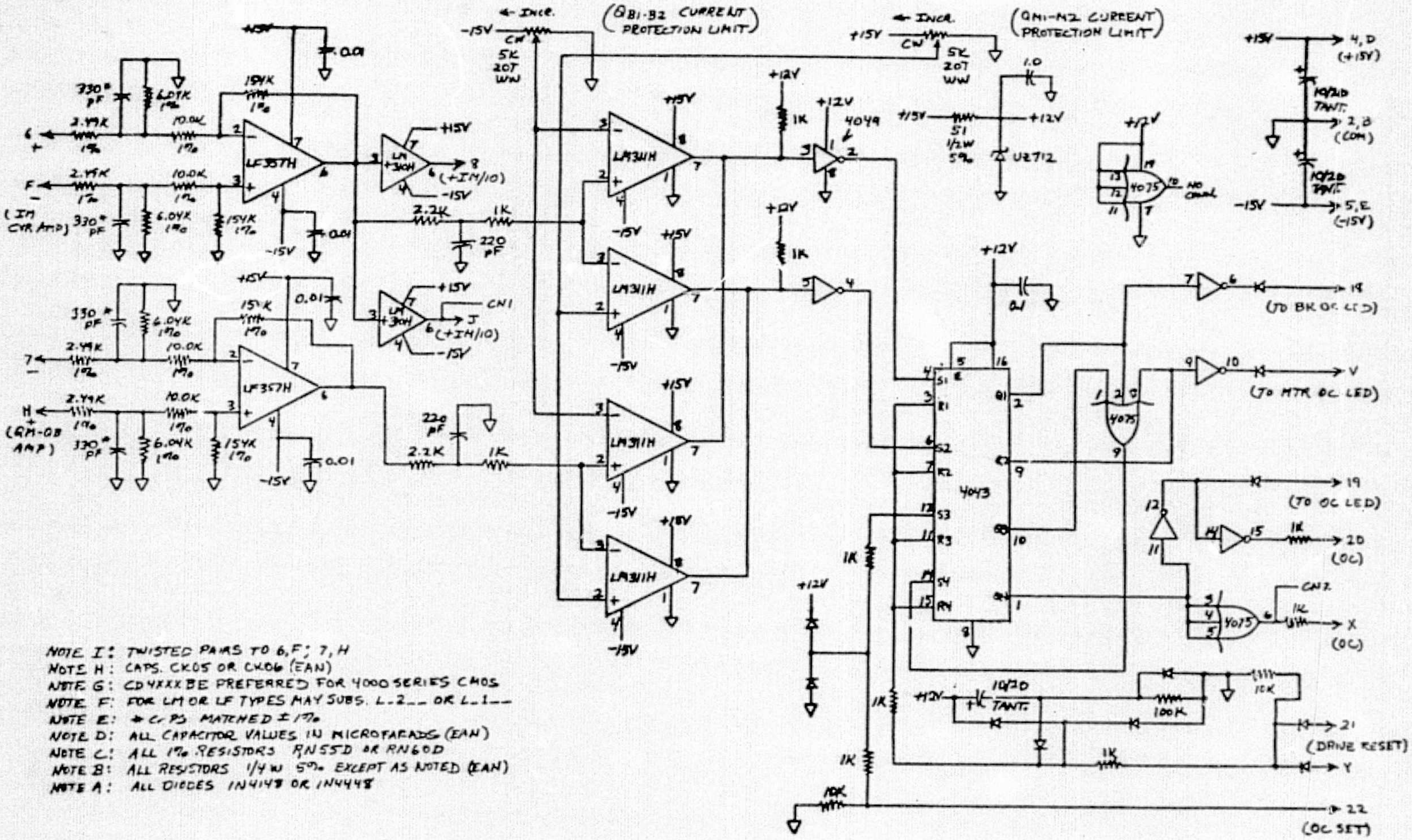
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±
MATERIAL
REF (AC-ORL) | CHG CONTROL
CONTR. NO.
DFTSMN DSGR A.H.B. 11-17-77
CHECKER
ENGR A.K. Barrett 11-17-77
APPD
APPD
DSGN ACTIVITY APPD
OTHER APPROVAL

Delco Electronics
GENERAL MOTORS CORPORATION SANTA BARBARA CALIF.

TITLE NASA SIX SWITCH BRIDGE CURRENT PROTECTION BOARD A12

SIZE C | CODE IDENT NO. 13160 | DWG NO. SK002077 | REV
SCALE | WEIGHT | SHEET 1 OF 1


ALL DIODES 1N4448
T1
T2
T3
T4
T5
T6
To J14-A
J14-B
To J14-G
To J14-J
To J14-C
To J14-D
To J14-H
To J14-J
J14-E
J14-F
To J14-I
To J14-J
1/2 DIP 1
1/2 DIP 2
DIP 3
1/2 QT1
1/2 QT3
40Ω 5W NI
10Ω 5W NI
OSC Input
DRIVE DISABLE
to +5V
GND
+5V
Vcc
L_1, L_2 = 6 Turns #26 on core F625-92-06
TYPE
HT1-6500-SB
SN5413N
1N4448
SN5402N
REF. RSK 21631
C_1 100μf @ 10V
C_2 .015μf @ 100V
Delco Electronics
GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF.
SCHEMATIC - ELECT.
R.F. DRIVE
A 15
AL Barr
8-12-71
SIZE B
CODE IDENT NO. 13160
DWG NO. SK002078



NOTE I: TWISTED PAIRS TO 6,F; 7,H
NOTE H: CAPS. CK05 OR CK06 (EAN)
NOTE G: CD4XXXBE PREFERRED FOR 4000 SERIES CMOS
NOTE F: FOR LM OR LF TYPES MAY SUBS. L-2__ OR L-1__
NOTE E: * CAPS MATCHED ± 1%
NOTE D: ALL CAPACITOR VALUES IN MICROFARADS (EAN)
NOTE C: ALL 1% RESISTORS RN55D OR RN60D
NOTE B: ALL RESISTORS 1/4 W 5% EXCEPT AS NOTED (EAN)
NOTE A: ALL DIODES IN4148 OR IN4448

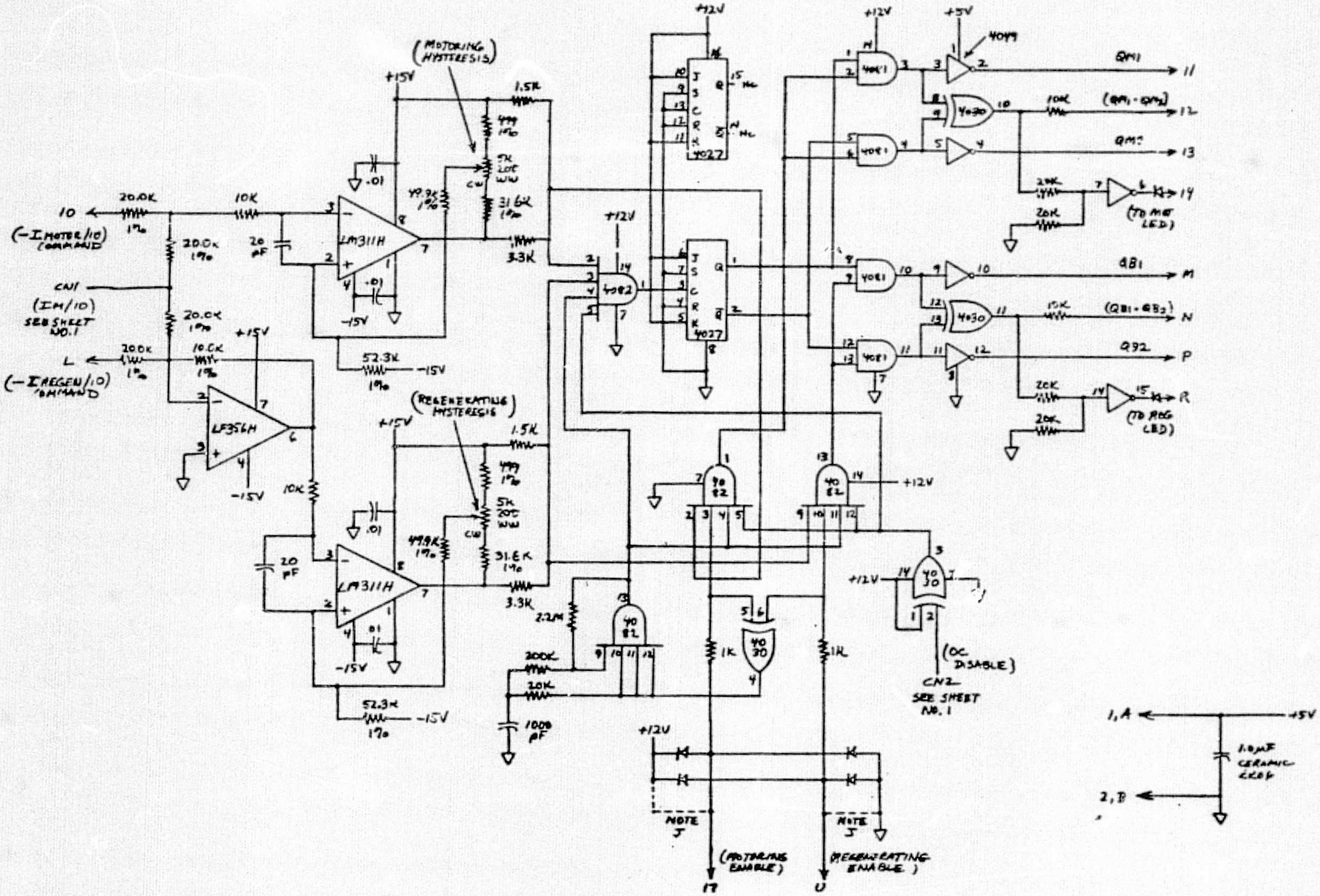
REV A 12-16-77

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±
MATERIAL
REF I/C DRL | CHG CONTROL
CONTR NO.
DFTSMN DSGR A.K.B. 12/3/77
CHECKER
ENGR A. K. Barnett 12/3/77
APPD
APPD
DSGN ACTIVITY APPD
OTHER APPROVAL

Delco Electronics
GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF.

TITLE NASA QM-QB CURRENT PROTECT, AND MODULATION A22

SIZE C | CODE IDENT NO 13160 | DWG NO. SK 002079 | REV A
SCALE | WEIGHT | SHEET 1 OF 2

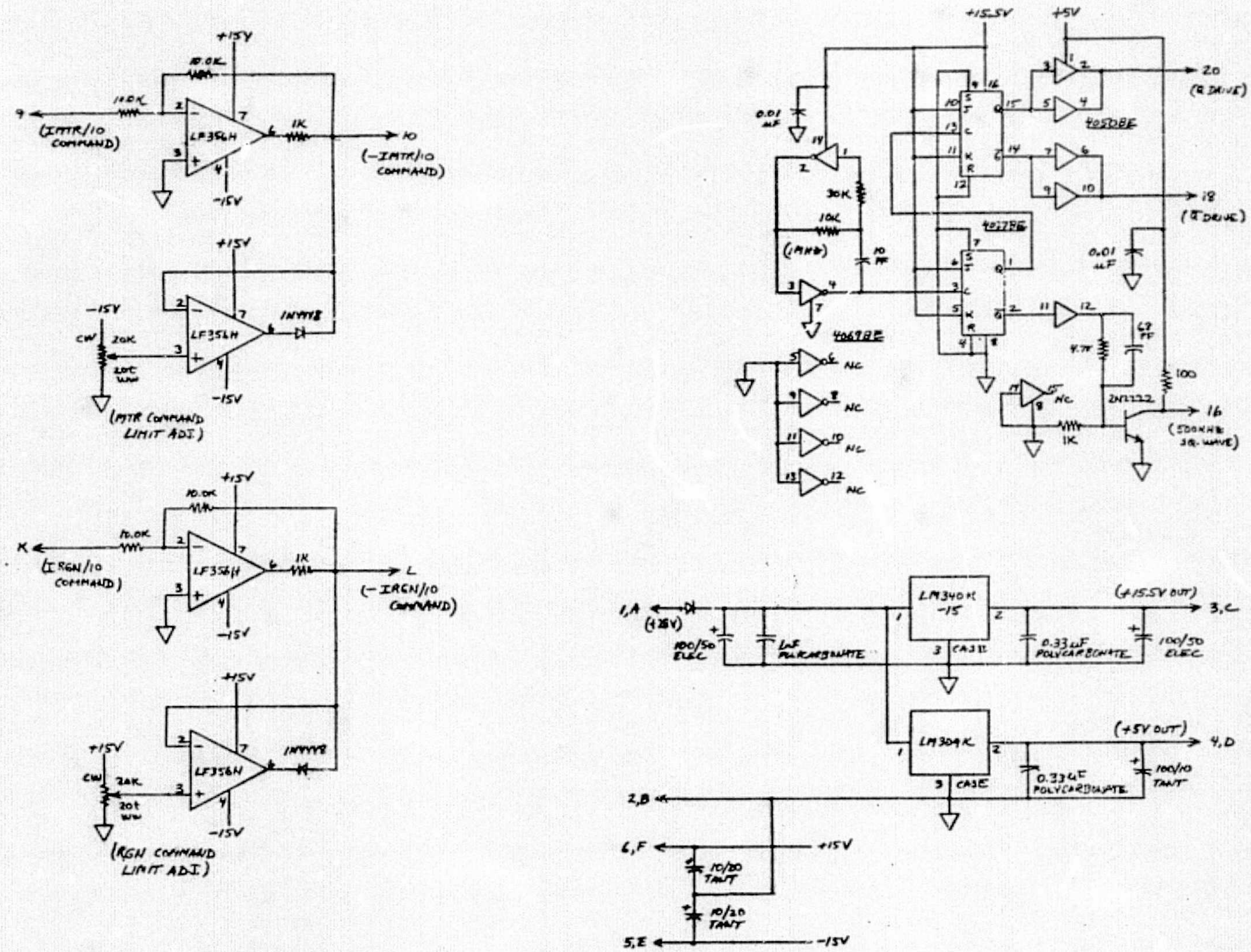


REV A 12-16-77

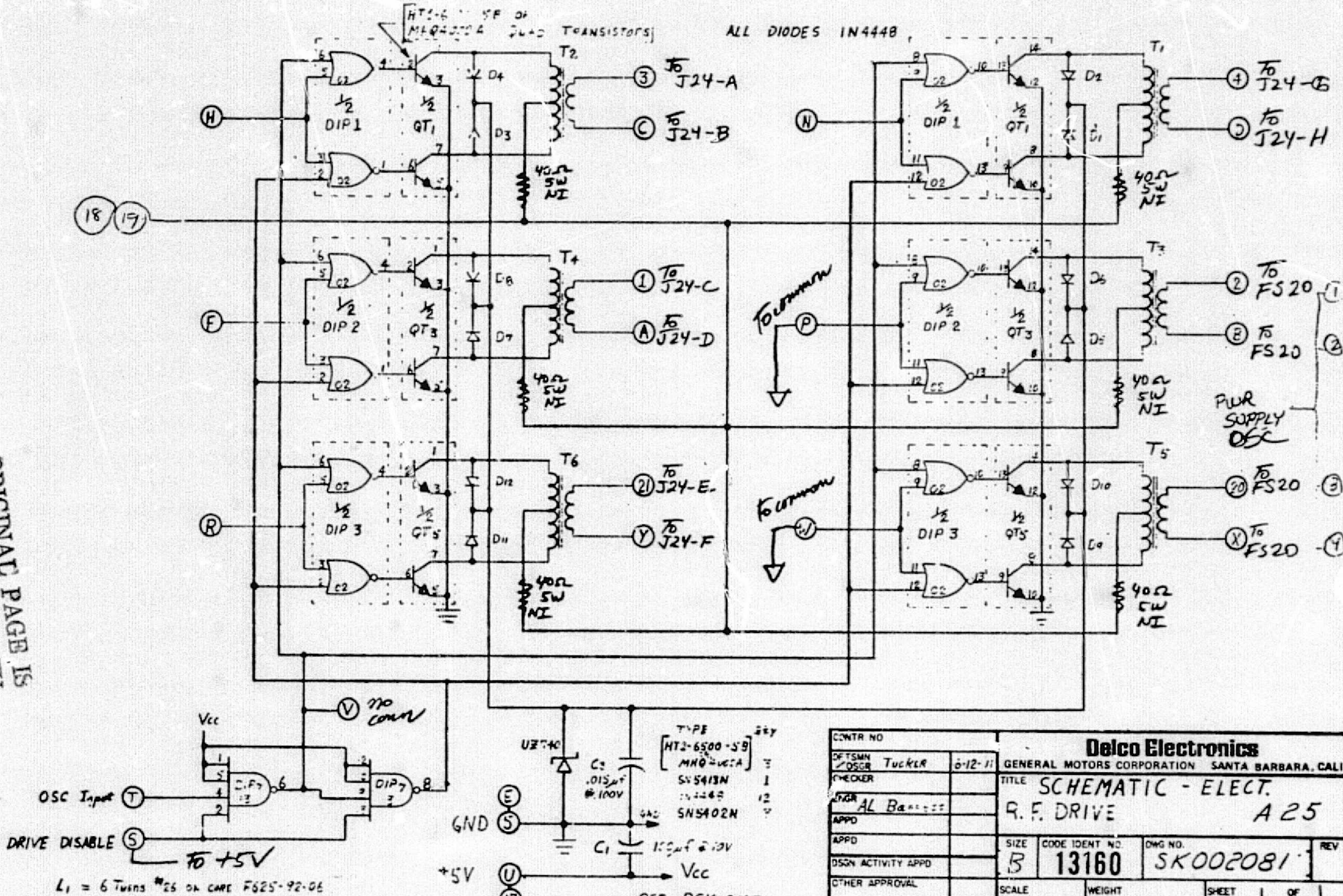
ALL NOTES ON SHEET NO. 1 APPLY

NOTE J: JUMPER FOR MOTORING ONLY (TEMPORARY)

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±	CONTR. NO.	Delco Electronics GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF
	DRAWN G.K.B. 12/3/77	TITLE NASA QM-QB CURRENT PROTECT. AND MODULATION A22
MATERIAL	CHECKER	
	ENGR [signature] 12/3/77	
	APPD	SIZE C · CODE IDENT NO. 13160 · DWG NO. SK 002079 · REV A
REF (AC ORL) · CHG CONTROL	DSGN ACTIVITY APPD	SCALE · WEIGHT · SHEET 2 OF 2
	OTHER APPROVAL	



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±	CONTR NO. DFTSMN/DSGN C.H.P. 12/16/77 CHECKER ENGR G.H. Cassett 12/6/77 APPD APPD DSGN ACTIVITY APPD OTHER APPROVAL	**Delco Electronics** GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF.
MATERIAL		TITLE NASA GM-G3 CONT. INTERFACE, Q-Q̄ DRIVE, +5V, +16V . A23
		SIZE C CODE IDENT NO 13160 DWG NO. SK02?080 REV
REF FAC DRL CHG CONTROL		SCALE WEIGHT SHEET 1 OF 1



CONTR NO		Delco Electronics GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF	
DFTSMN / DSGR	Tucker 6-12-71	TITLE SCHEMATIC - ELECT. R. F. DRIVE A25	
CHECKER			
ENGR	AL Ba[illegible]		
APPD			
APPD		SIZE B	CODE IDENT NO. 13160
DSGN ACTIVITY APPD		DWG NO. SK002081	REV
OTHER APPROVAL		SCALE	WEIGHT
		SHEET 1 OF 1	

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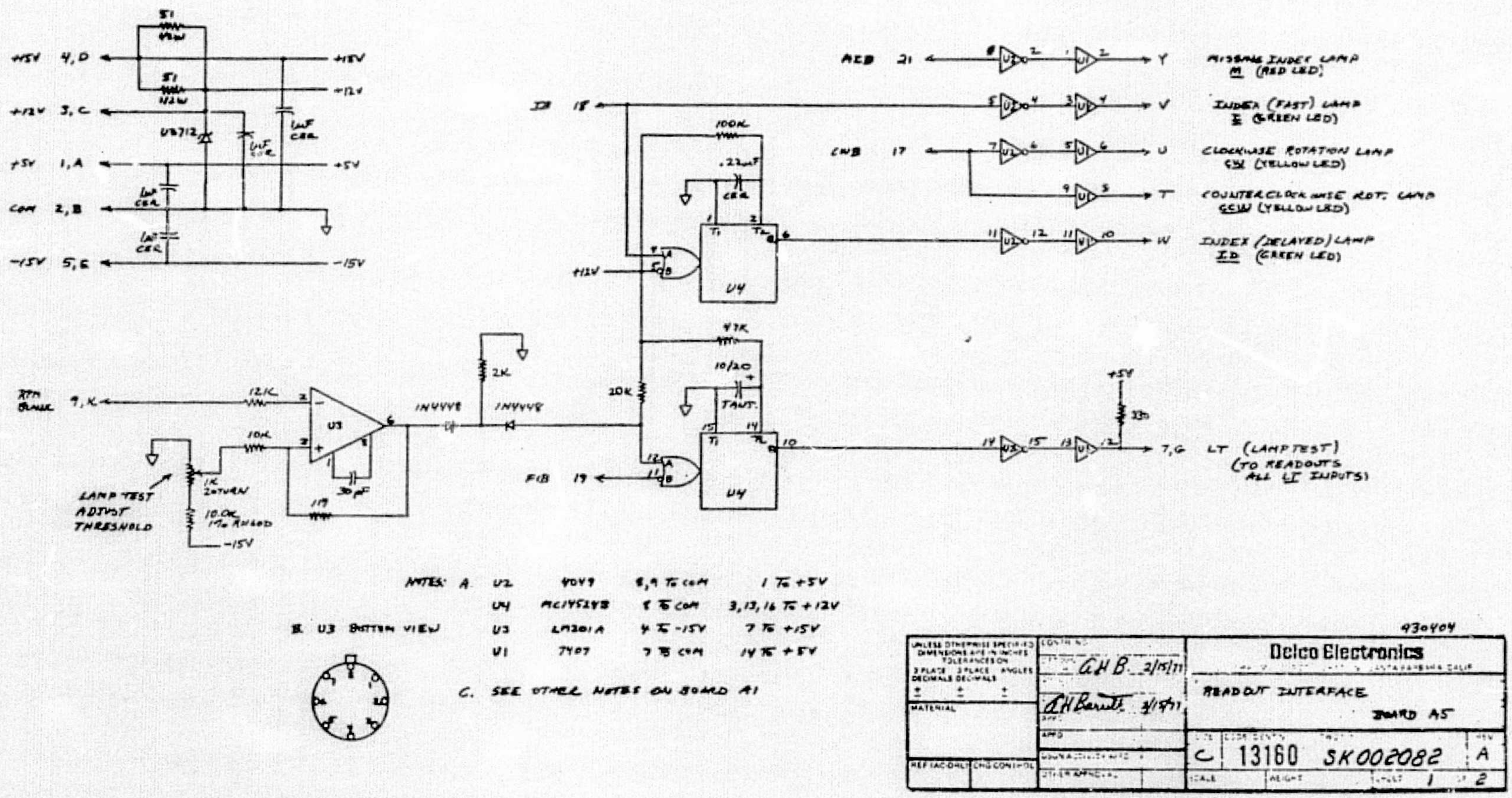
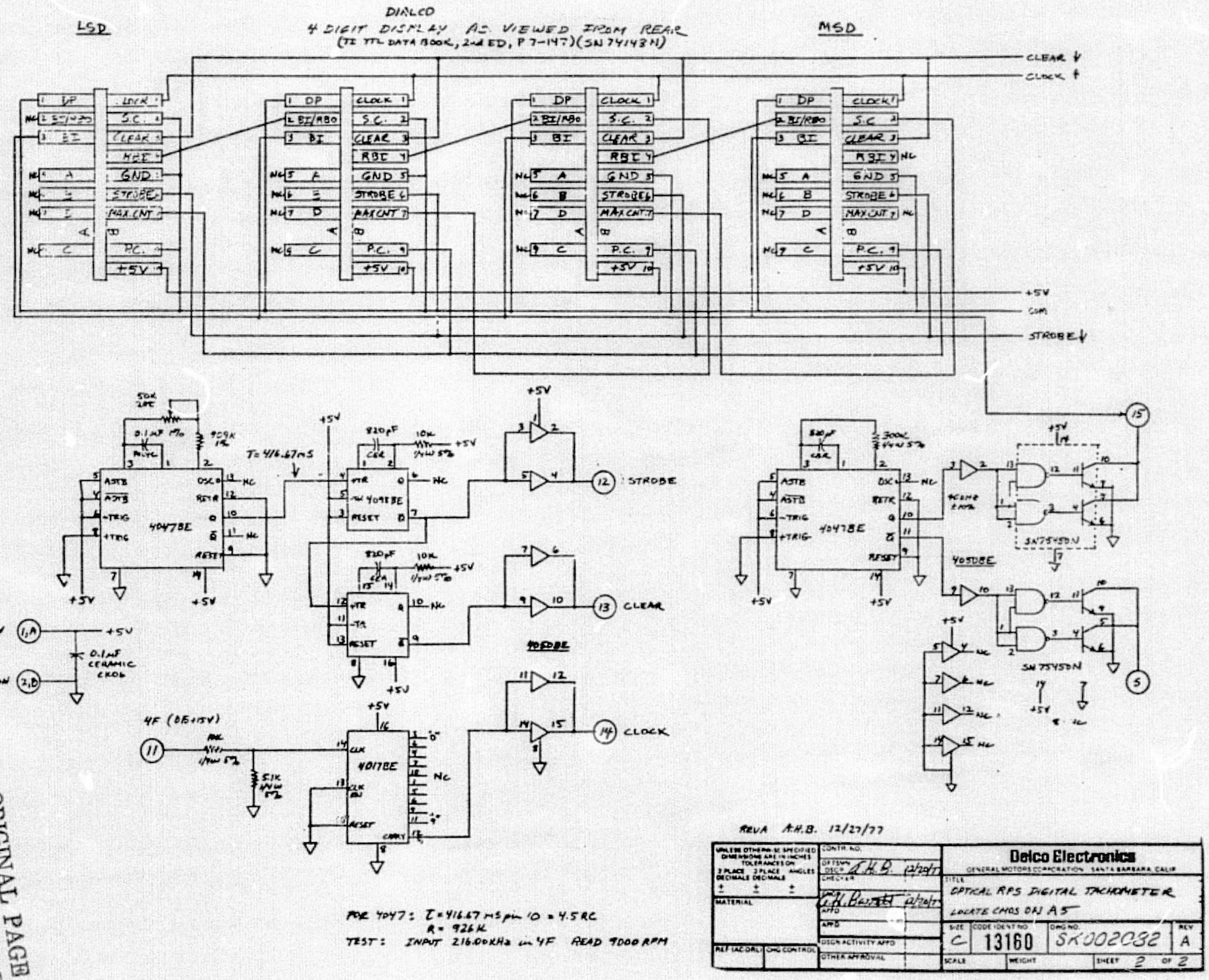
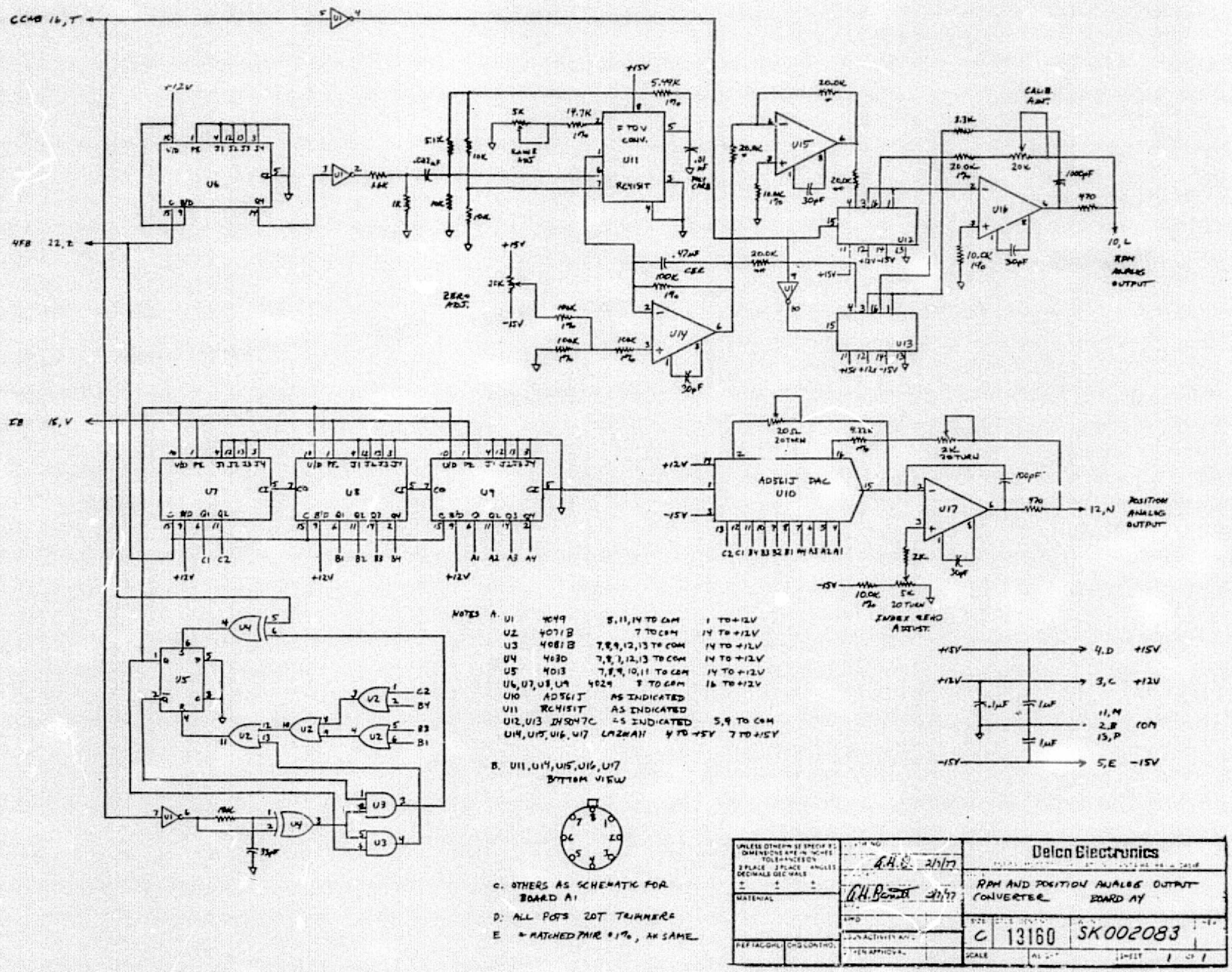
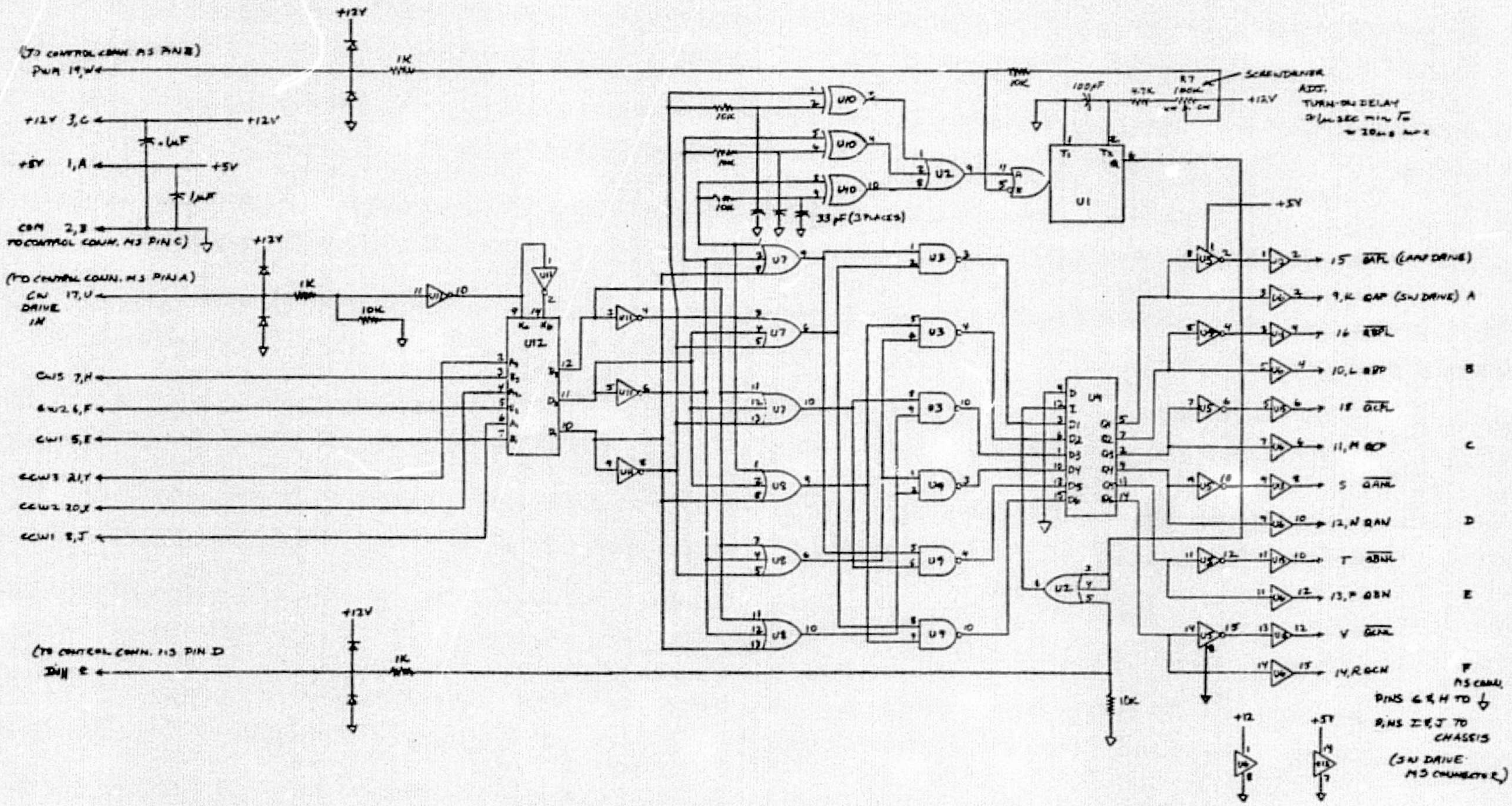

+15V 4,D
+12V 3,C
+5V 1,A
COM 2,B
-15V 5,E
UZ712
RPM BLANK 9,K
LAMP TEST ADJUST THRESHOLD
1N4448
MEB 21
ID 18
CWB 17
F/B 19
MISSING INDEX LAMP M (RED LED)
INDEX (FAST) LAMP I (GREEN LED)
CLOCKWISE ROTATION LAMP CW (YELLOW LED)
COUNTERCLOCKWISE ROT. LAMP CCW (YELLOW LED)
INDEX (DELAYED) LAMP ID (GREEN LED)
7,G LT (LAMP TEST) (TO READOUTS ALL LT INPUTS)
NOTES: A. U2 4049 8,9 TO COM 1 TO +5V
U4 MC14528B 8 TO COM 3,13,16 TO +12V
U3 LM201A 4 TO -15V 7 TO +15V
U1 7407 7 TO COM 14 TO +5V
B. U3 BOTTOM VIEW
C. SEE OTHER NOTES ON BOARD A1
430404
Delco Electronics
READOUT INTERFACE
BOARD A5
C 13160 SK002082 A
1 2


DIALCO
4 DIGIT DISPLAY AS VIEWED FROM REAR
(TI TTL DATA BOOK, 2nd ED, P 7-147)(SN 74143N)
LSD
MSD
CLEAR
CLOCK
DP
BI/RBO
BI
A
B
D
C
CLOCK
S.C.
CLEAR
RBI
GND
STROBE
MAX CNT
P.C.
+5V
+5V
COM
STROBE
4047BE
4098BE
4017BE
4050BE
SN75450N
T = 416.67 mS
820pF
10K
+5V
STROBE
CLEAR
CLOCK
NC
+5V
COMMON
0.1μF
CERAMIC
CK06
4F (0E+15V)
5.1K
1/4W 5%
REV A A.H.B. 12/27/77
FOR 4047: T = 416.67 mS pin 10 = 4.5RC
R = 926K
TEST: INPUT 216.00kHz in 4F READ 9000 RPM
Delco Electronics
GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF.
OPTICAL RPS DIGITAL TACHOMETER
LOCATE CMOS ON A5
C
13160
SK002082
A
SHEET 2 OF 2


CCWB 16, T
4FB 22, Z
FB 15, V
F TO V CONV.
U11
RC4151T
ZERO ADJ.
CALIB. ADJ.
10, L
RPM ANALOG OUTPUT
AD561J DAC
U10
12, N
POSITION ANALOG OUTPUT
INDEX ZERO ADJUST.
4, D +15V
3, C +12V
11, M
2, B COM
13, P
5, E −15V
NOTES A. U1 4049 5, 11, 14 TO COM 1 TO +12V
U2 4071B 7 TO COM 14 TO +12V
U3 4081B 7, 8, 9, 12, 13 TO COM 14 TO +12V
U4 4030 7, 8, 9, 12, 13 TO COM 14 TO +12V
U5 4013 7, 8, 9, 10, 11 TO COM 14 TO +12V
U6, U7, U8, U9 4029 8 TO COM 16 TO +12V
U10 AD561J AS INDICATED
U11 RC4151T AS INDICATED
U12, U13 IH5047C AS INDICATED 5, 9 TO COM
U14, U15, U16, U17 LM208AH 4 TO −15V 7 TO +15V
B. U11, U14, U15, U16, U17 BOTTOM VIEW
C. OTHERS AS SCHEMATIC FOR BOARD A1
D. ALL POTS 20T TRIMMERS
E. * MATCHED PAIR ±1%, ** SAME
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS 3 PLACE DECIMALS ANGLES
MATERIAL
G.H.B. 2/1/77
G.H. Barrett 2/1/77
Delco Electronics
RPM AND POSITION ANALOG OUTPUT CONVERTER BOARD A4
C 13160 SK002083
SCALE
SHEET 1 OF 1



NOTES: A.

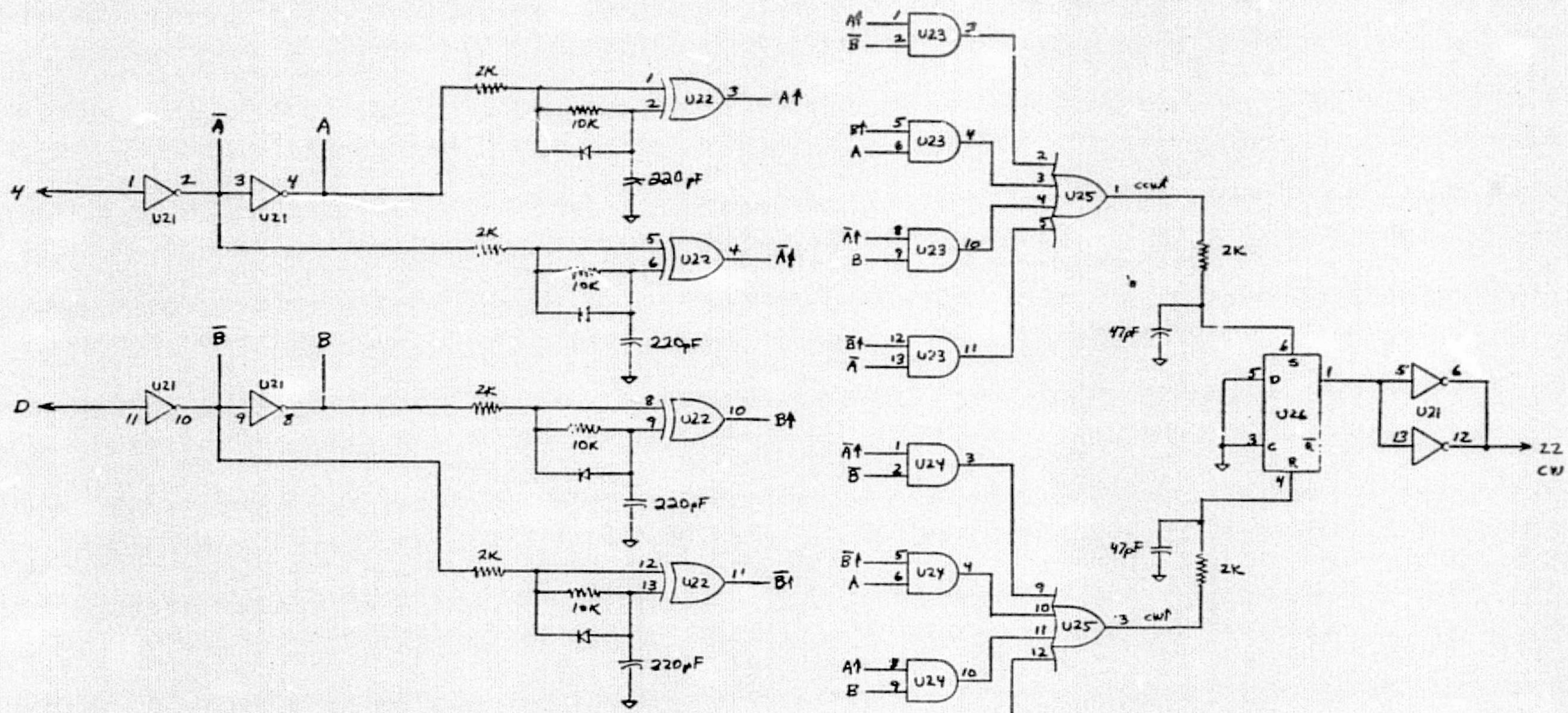
U11	MC14584B	7,11,13 TO COM	14 TO +12V
U5	4049	8 TO COM	1 TO +12V
U6	4050	8 TO COM	1 TO +5V
U3, U9	4011	7 TO COM	12,13,14 TO +12V
U10	4030	7 TO COM	12,13,14 TO +12V
U7, U8	4075B	7 TO COM	14 TO +12V
U2	4075B	7 TO COM	11,12,13,14 TO +12V
U4	MC14502B	8 TO COM	16 TO +12V
U12	MC14519B or 4019	1,8,15 TO COM	16 TO +12V
U1	MC14528B	8,11,12 TO COM	3,13,16 TO +12V
U13	7407 (TTL) 7 TO COM	14 TO +5V	

B. ALL IC'S CMOS HANDLE WITH CARE

C. OTHER NOTES - SEE BOARD A1 SCHEMATIC DIAGRAM

D. ALL DIODES 1N4458, 1N4444, OR 1N4148

Delco Electronics	
SIX SWITCH BRIDGE LOW LEVEL INTERFACE BOARD A3	
DRAWN AKB 7/4/77	AH Bennett 2/3/77
SIZE C	13160
SK002084	REV A
SHEET 1 OF 2	



U21	4584B	7 TO COM	14 TO +12V
U22	4030	7 TO COM	14 TO +12V
U23, U24	4081B	7 TO COM	14 TO +12V
U25	4072B	7 TO COM	14 TO +12V
U26	4013	3,5,7,8,9,10,11 TO COM	14 TO +12V

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± ANGLES ±

MATERIAL

REF (AC-DRL) CHG CONTROL

CONTR NO

DFTSMN DSGN G.H.B. 4/9/77

CHECKER

ENG G.H. Barnabi 4/9/77

APPD

APPD

DSGN ACTIVITY APPD

OTHER APPROVAL

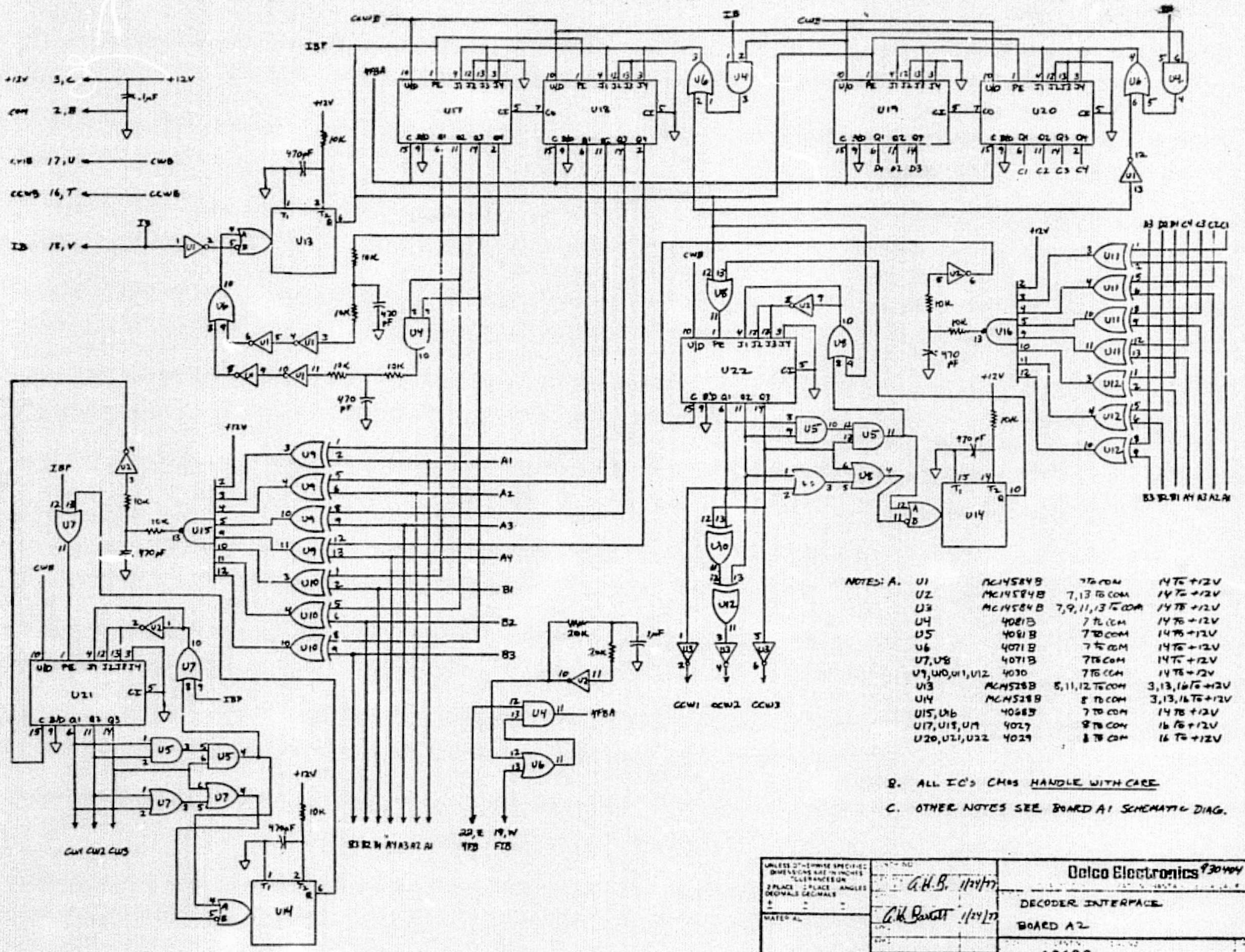
Delco Electronics

GENERAL MOTORS CORPORATION SANTA BARBARA, CALIF

TITLE MOD. DIRECTION OF TRAVEL BOARD A3

SIZE | CODE IDENT NO 13160 | DWG NO. SK002084 | REV A

SCALE | WEIGHT | SHEET 2 OF 2



NOTES: A.

U1	MC14584B	7 TO COM	14 TO +12V
U2	MC14584B	7,13 TO COM	14 TO +12V
U3	MC14584B	7,9,11,13 TO COM	14 TO +12V
U4	4081B	7 TO COM	14 TO +12V
U5	4081B	7 TO COM	14 TO +12V
U6	4071B	7 TO COM	14 TO +12V
U7,U8	4071B	7 TO COM	14 TO +12V
U9,U10,U11,U12	4030	7 TO COM	14 TO +12V
U13	MC14528B	8,11,12 TO COM	3,13,16 TO +12V
U14	MC14528B	8 TO COM	3,13,16 TO +12V
U15,U16	4068B	7 TO COM	14 TO +12V
U17,U18,U19	4027	8 TO COM	16 TO +12V
U20,U21,U22	4029	8 TO COM	16 TO +12V

B. ALL IC'S CMOS HANDLE WITH CARE

C. OTHER NOTES SEE BOARD A1 SCHEMATIC DIAG.

Delco Electronics 930404

G.H.B. 1/24/77

G.K. Barrett 1/24/77

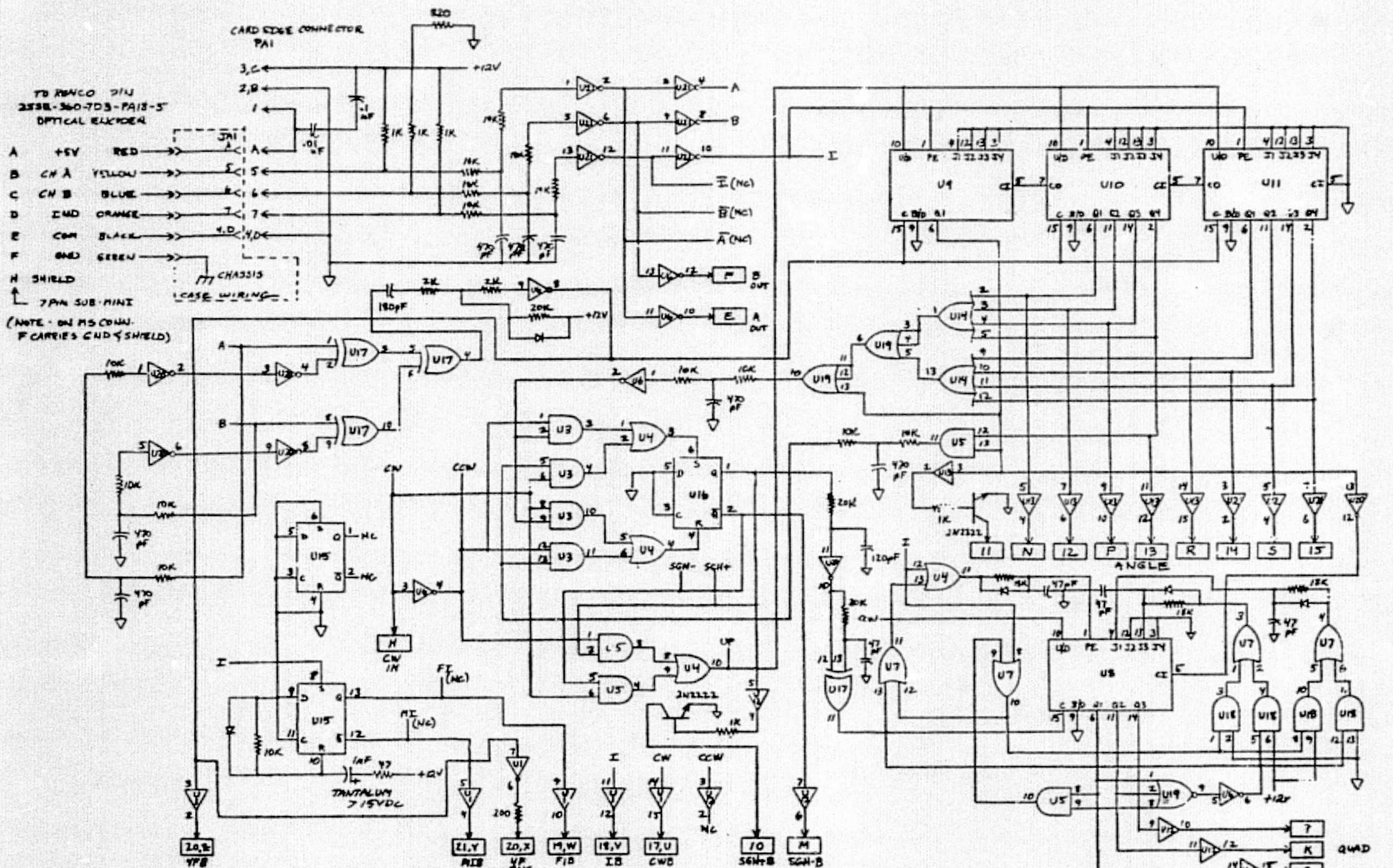
DECODER INTERFACE

BOARD A2

C 13160 SK002085

SHEET 1 OF 1

DELCO ELECTRONICS DIVISION • SANTA BARBARA OPERATIONS • GENERAL MOTORS CORPORATION



NOTES:

A.

U20,U21	MC14584B	7 TO COM	14 TO +12V
U6	MC14584B	5,7,9,11,13 TO COM	14 TO +12V
U3,U5,U18	4081B	7 TO COM	14 TO +12V
U4,U7	4071B	7 TO COM	14 TO +12V
U19	4075B	7 TO COM	14 TO +12V
U14	4072B	7 TO COM	14 TO +12V
U1,U12,U13	4050	8 TO COM	1 TO +5V (EX U1 TO +12V)
U2	4050	8,9,11,14 TO COM	1 TO +5V
U17	4030	7 TO COM	14 TO +12V
U15	4013	3,4,5,6,7 TO COM	14 TO +12V
U16	4013	7,8,9,10,11 TO COM	14 TO +12V
U8,U9,U10,U11	4029	8 TO COM	16 TO +12V

B. ALL RESISTORS 1/4W 5%

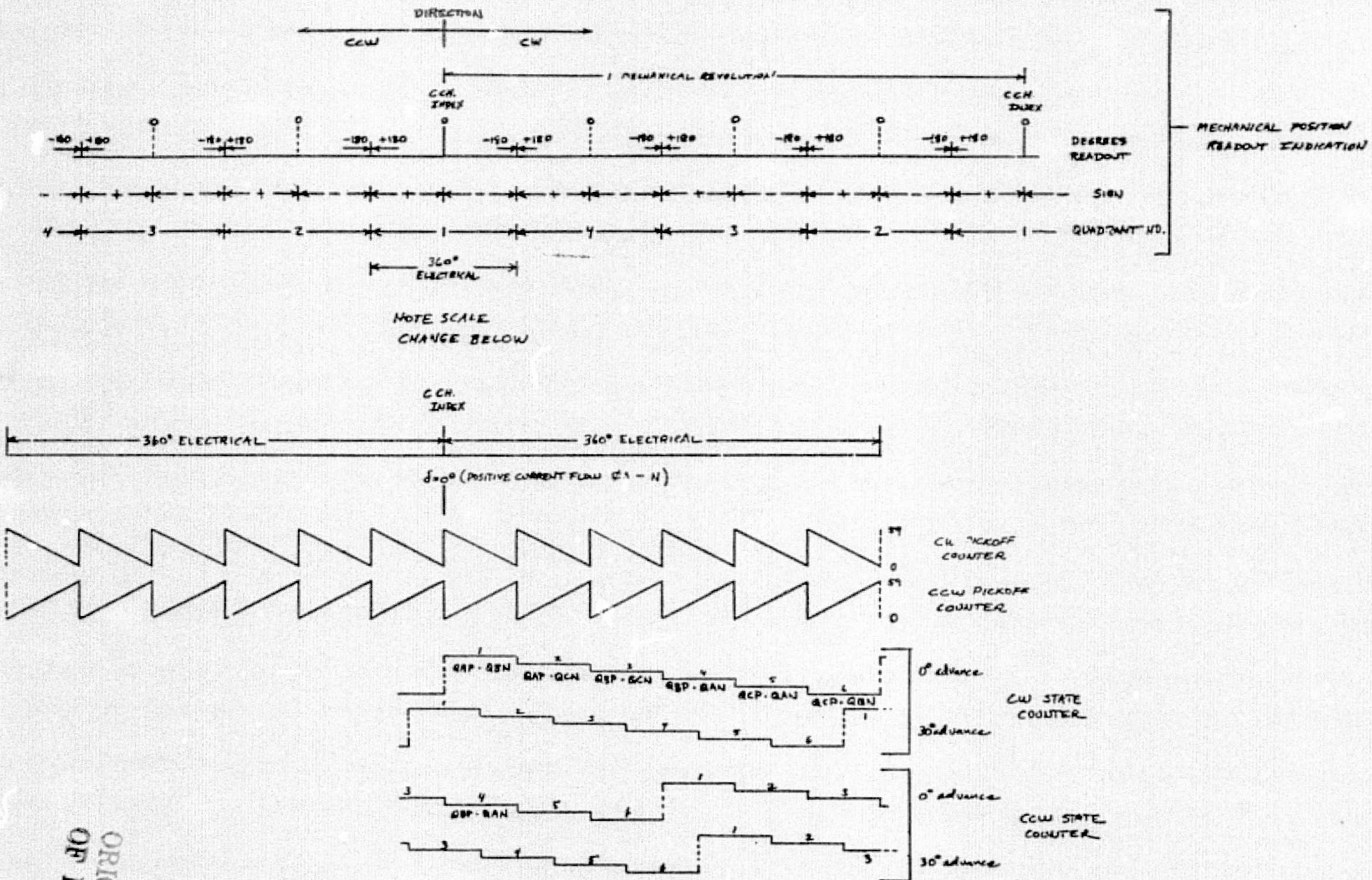
C. ALL CAPACITORS CK05 (CERAMIC) UNLESS OTHERWISE INDICATED

D. ALL DIODES 1N4448, 1N4444 OR 1N4148

E. ALL IC'S CMOS <u>HANDLE WITH CARE</u>

F. OUTPUTS ARE CARD EDGE ON PA1 UNLESS OTHERWISE INDICATED, NUMBERS ON COMPONENT (TOP) SIDE LETTERS ON UNDER SIDE EXAMPLE $\boxed{1,A}$

DRAWN: G.H.B. 1/18/77	**Delco Electronics**
A.H. Barrett 1/18/77	ENCODER INTERFACE / POSITION INDICATOR BOARD A1
SIZE: C	13160
DWG NO: S-002086	A
SHEET 1 OF 1	



Delco Electronics 930404

POWER SWITCH DRIVE SIGNAL DECODER AND INDICATOR TIMING DIAGRAM

A.H.B. 1/24/77

A.H. Barrett 1/24/77

C 13160 SK002087

APPENDIX B

GEAR DESIGN DATA

This appendix contains detailed design data on the gears used in the differential gearbox.

Gleason Works

R1 Zerol Bevel

ZEROL BEVEL GEAR DIMENSIONS NO. 474,675 FORM K DATE 10/25/74

Delco Electronics
~~GLEASON WORKS ROCHESTER~~

GLEASON WORKS ROCHESTER, NEW YORK 14603 U.S.A.

	PINION	GEAR
NUMBER OF TEETH	16	60
PART NUMBER		
DIAMETRAL PITCH		13,333
FACE WIDTH	0,600"	0,600"
PRESSURE ANGLE	20D 0M	
SHAFT ANGLE	90D 0M	
TRANSVERSE CONTACT RATIO . .		1,318
FACE CONTACT RATIO		0,000
MODIFIED CONTACT RATIO . . .		1,318
OUTER CONE DISTANCE		2,329"
MEAN CONE DISTANCE		2,029"
PITCH DIAMETER	1,200"	4,500"
CIRCULAR PITCH	0,236"	
WORKING DEPTH	0,150"	
WHOLE DEPTH	0,166"	0,166"
CLEARANCE	0,016"	0,016"
ADDENDUM	0,107"	0,043"
DEDENDUM	0,059"	0,123"

	PINION	GEAR
THEORETICAL CUTTER RADIUS .		
CUTTER RADIUS	3,000"	
CALC. GEAR FINISH. PT. WIDTH		0,053"
GEAR FINISHING POINT WIDTH .		0,055"
ROUGHING POINT WIDTH	0,045"	0,055"
OUTER SLOT WIDTH	0,049"	0,055"
MEAN SLOT WIDTH	0,049"	0,055"
INNER SLOT WIDTH	0,046"	0,055"
FINISHING CUTTER BLADE POINT	0,030"	0,030"
STOCK ALLOWANCE	0,001"	"0,000"
MAX. RADIUS-CUTTER BLADES .	0,025"	0,031"
MAX. RADIUS-MUTILATION . . .	0,044"	0,059"
MAX. RADIUS-INTERFERENCE . .	0,018"	0,040"
CUTTER EDGE RADIUS	0,010"	0,010"
CALC. CUTTER NUMBER	0	0
MAX. NO. BLADES IN CUTTER .		31,285
CUTTER BLADES REQUIRED . . .	STD DEPTH	STD DEPTH

		GEAR
GEAR ANGULAR FACE - CONCAVE		11D 12M
GEAR ANGULAR FACE - CONVEX .		11D 45M
GEAR ANGULAR FACE - TOTAL .		11D 30M

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ZEROL IS A TRADEMARK OF THE GLEASON WORKS

		PINION		GEAR
OUTSIDE DIAMETER		1,407"		4,522"
PITCH APEX TO CROWN		2,222"		0,559"
MEAN CIRCULAR THICKNESS . .		0,123"		0,078"
OUTER NORMAL TOP LAND . . .		0,033"		0,056"
MEAN NORMAL TOP LAND		0,044"		0,059"
INNER NORMAL TOP LAND . . .		0,055"		0,055"
PITCH ANGLE		14D 56M		75D 4M
FACE ANGLE OF BLANK		19D 33M		78D 7M
ROOT ANGLE		11D 53M		70D 27M
DEDENDUM ANGLE		3D 3M		4D 37M
OUTER SPIRAL ANGLE				5D 22M
MEAN SPIRAL ANGLE				0D 0M
INNER SPIRAL ANGLE			-	6D 14M
HAND OF SPIRAL	LH		RH	
DRIVING MEMBER	PIN			
DIRECTION OF ROTATION-DRIVER	REV			
OUTER NORMAL BACKLASH . . .	MIN	0,002"	MAX	0,004"
TOOTH TAPER	DPLX			
CUTTING METHOD			SB	
GEAR TYPE				GENERATED
FACE IN PERCENT OF CONE DIST				25,766

		PINION		GEAR
GEOMETRY FACTOR-STRENGTH-J .		0,1862		0,1631
STRENGTH FACTOR-Q		104,116		31,686
SIZE FACTOR - KS		0,523		
FACTOR	KI	1,5169		
STRENGTH BALANCE DESIRED . .	STRS			
STRENGTH BALANCE OBTAINED .	TPLD			0,100
GEOMETRY FACTOR-DURABILITY-I		0,0597		
DURABILITY FACTOR-Z		17608,63		9093,06
GEOMETRY FACTOR-SCORING-G .*		0,009598		
SCORING FACTOR - X		1,0157		
ROOT LINE FACE WIDTH		0,600"		0,600"
PROFILE SLIDING FACTOR . . .		0,00159		0,00264
RATIO OF INVOLUTE/OUTER CONE		2,019		
AXIAL FACTOR-DRIVER CW . . .	OUT	0,179	OUT	0,179
AXIAL FACTOR-DRIVER CCW . .	OUT	0,179	OUT	0,179
SEPARATING FACTOR-DRIVER CW	SEP	0,673	SEP	0,048
SEPARATING FACTOR-DRIVER CCW	SEP	0,673	SEP	0,048
DUPLEX SUM OF DEDENDUM ANG .				
ROUGHING RADIAL		3,622"		-

*THIS FACTOR IS USED IN THE 1966 SCORING FORMULA

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OF POOR QUALITY

Gleason Works

RZ [illegible] Bevel

SPIROL BEVEL GEAR DIMENSIONS — NO. 474,213 — FORM K — DATE 8/23/74

CUSTOMER = DELCO ELECTRONICS

	PINION	GEAR
NUMBER OF TEETH	26	39
PART NUMBER		
DIAMETRAL PITCH		9.630
FACE WIDTH	0.630"	0.630"
PRESSURE ANGLE	20° 0'	
SHAFT ANGLE	90° 0'	
TRANSVERSE CONTACT RATIO . .		1.451
FACE CONTACT RATIO		0.000
MODIFIED CONTACT RATIO . . .		1.451
OUTER CONE DISTANCE		2.430"
MEAN CONE DISTANCE		2.119"
PITCH DIAMETER	2.700"	4.050"
CIRCULAR PITCH	0.326"	
WORKING DEPTH	0.208"	
WHOLE DEPTH	0.220"	0.229"
CLEARANCE	0.022"	0.022"
ADDENDUM	0.130"	0.077"
DEDENDUM	0.099"	0.152"

	PINION	GEAR
THEORETICAL CUTTER RADIUS .		
CUTTER RADIUS	3.000"	
CALC. GEAR FINISH. PT. WIDTH		0.066"
GEAR FINISHING POINT WIDTH .		0.065"
ROUGHING POINT WIDTH	0.065"	0.055"
OUTER SLOT WIDTH	0.080"	0.065"
MEAN SLOT WIDTH	0.080"	0.065"
INNER SLOT WIDTH	0.076"	0.065"
FINISHING CUTTER BLADE POINT	0.050"	0.040"
STOCK ALLOWANCE	0.011"	0.010"
MAX. RADIUS-CUTTER BLADES .	0.053"	0.039"
MAX. RADIUS-MUTILATION . . .	0.060"	0.059"
MAX. RADIUS-INTERFERENCE . .	0.026"	0.000"
CUTTER EDGE RADIUS	0.020"	0.020"
CALC. CUTTER NUMBER	0	0
MAX. NO. BLADES IN CUTTER .		
CUTTER BLADES REQUIRED . . .	STD DEPTH	STD DEPTH

PINION ANGULAR FACE = CONCAVE
GEAR ANGULAR FACE = CONVEX .
GEAR ANGULAR FACE = TOTAL .

RELEASED BY =

"SPIROL" IS A TRADEMARK OF THE GLEASON WORKS

		PINION		GEAR
OUTSIDE DIAMETER		2.917"		4.136"
PITCH APEX TO CROWN		1.953"		1.286"
MEAN CIRCULAR THICKNESS . .		0.148"		0.131"
OUTER NORMAL TOP LAND . . .		0.057"		0.088"
MEAN NORMAL TOP LAND		0.065"		0.092"
INNER NORMAL TOP LAND . . .		0.072"		0.087"
PITCH ANGLE		33° 41'		56° 19'
FACE ANGLE OF BLANK		39° 20'		60° 42'
ROOT ANGLE		29° 18'		50° 40'
DEDENDUM ANGLE		4° 24'		5° 38'
OUTER SPIRAL ANGLE				5° 34'
MEAN SPIRAL ANGLE				0° 3'
INNER SPIRAL ANGLE				- 6° 33'
HAND OF SPIRAL	LH		RH	
DRIVING MEMBER	PIN			
DIRECTION OF ROTATION-DRIVER	REV			
OUTER NORMAL BACKLASH . . .	MIN	0.003"	MAX	0.005"
TOOTH TAPER	DPLX			
CUTTING METHOD			SB	
GEAR TYPE				GENERATED
FACE WIDTH IN PERCENT OF CONE DISTANCE . .				25.897

		PINION		GEAR
GEOMETRY FACTOR-STRENGTH-J .		0.2192		0.2184
STRENGTH FACTOR-G		29.327		19.424
SIZE FACTOR - KS		0.568		
FACTOR	KI	1.3785		
STRENGTH BALANCE DESIRED . .	STRS			
STRENGTH BALANCE OBTAINED .	STRS			0.009
GEOMETRY FACTOR-DURABILITY-I		0.0657		
DURABILITY FACTOR-Z		7282.		5946.
GEOMETRY FACTOR-SCORING-G .*		0.004531		
SCORING FACTOR - X		0.5547		
ROOT LINE FACE WIDTH		0.630"		0.630"
PROFILE SLIDING FACTOR . . .		0.002523		0.002307
RATIO OF INVOLUTE/OUTER CONE		1.949		
AXIAL FACTOR-DRIVER CW . . .	OUT	0.172	OUT	0.172
AXIAL FACTOR-DRIVER CCW . .	OUT	0.172	OUT	0.172
SEPARATING FACTOR-DRIVER CW	SEP	0.258	SEP	0.115
SEPARATING FACTOR-DRIVER CCW	SEP	0.258	SEP	0.115
DUPLEX SUM OF DEDENDUM ANG .				
ROUGHING RADIAL		3.673"		

*THIS FACTOR IS USED IN THE 1966 SCORING FORMULA

GLEASON WORKS ROCHESTER, NEW YORK 14603 U.S.A.

DELCO ELECTRONICS DIVISION • SANTA BARBARA OPERATIONS • GENERAL MOTORS CORPORATION

Gleason Works

GLEASON WORKS ROCHESTER, NEW YORK 14603 U.S.A.

DELCO ELECTRONICS DIVISION • SANTA BARBARA OPERATIONS • GENERAL MOTORS CORPORATION

1ST & 2ND Differential

ZEROL BEVEL GEAR DIMENSIONS NO. 474,200 FORM K DATE 8/26/74

CUSTOMER = DELCO ELECTRONICS

	PINION	GEAR
NUMBER OF TEETH	29	29
PART NUMBER		
DIAMETRAL PITCH		10.357
FACE WIDTH	0.515"	0.515"
PRESSURE ANGLE	20° 0'	
SHAFT ANGLE	90° 0'	
TRANSVERSE CONTACT RATIO . . .		1.477
FACE CONTACT RATIO		0.000
MODIFIED CONTACT RATIO		1.477
OUTER CONE DISTANCE		1.980"
MEAN CONE DISTANCE		1.722"
PITCH DIAMETER	2.800"	2.800"
CIRCULAR PITCH	0.303"	
WORKING DEPTH	0.193"	
WHOLE DEPTH	0.213"	0.213"
CLEARANCE	0.020"	0.020"
ADDENDUM	0.097"	0.097"
DEDENDUM	0.117"	0.117"

	PINION	GEAR
THEORETICAL CUTTER RADIUS .		
CUTTER RADIUS	3.000"	
CALC. GEAR FINISH. PT. WIDTH		0.068"
GEAR FINISHING POINT WIDTH .		0.070"
ROUGHING POINT WIDTH	0.050"	0.060"
OUTER SLOT WIDTH	0.065"	0.070"
MEAN SLOT WIDTH	0.063"	0.070"
INNER SLOT WIDTH	0.060"	0.070"
FINISHING CUTTER BLADE POINT	0.040"	0.040"
STOCK ALLOWANCE	0.010"	0.010"
MAX. RADIUS-CUTTER BLADES .	0.038"	0.046"
MAX. RADIUS-MUTILATION . . .	0.050"	0.068"
MAX. RADIUS-INTERFERENCE . .	0.030"	0.030"
CUTTER EDGE RADIUS	0.020"	0.020"
CALC. CUTTER NUMBER	0	0
MAX. NO. BLADES IN CUTTER .		
CUTTER BLADES REQUIRED . . .	STD DEPTH	STD DEPTH

MEAN ANGULAR FACE - CONCAVE
MEAN ANGULAR FACE - CONVEX .
MEAN ANGULAR FACE - TOTAL .

RELEASED BY - DRL

- [illegible] IS [illegible] MARK OF THE GLEASON WORKS

	PINION	GEAR
OUTSIDE DIAMETER	2.937"	2.937"
PITCH APEX TO CROWN	1.332"	1.332"
MEAN CIRCULAR THICKNESS . .	0.133"	0.128"
OUTER NORMAL TOP LAND . . .	0.073"	0.067"
MEAN NORMAL TOP LAND	0.077"	0.072"
INNER NORMAL TOP LAND . . .	0.080"	0.070"
PITCH ANGLE	45° 0'	45° 0'
FACE ANGLE OF BLANK	50° 41'	50° 41'
ROOT ANGLE	39° 19'	39° 19'
DEDENDUM ANGLE	5° 41'	5° 41'
OUTER SPIRAL ANGLE		4° 36'
MEAN SPIRAL ANGLE		0° 0'
INNER SPIRAL ANGLE		- 5° 21'
HAND OF SPIRAL	LH	RH
DRIVING MEMBER	PIN	
DIRECTION OF ROTATION-DRIVER	REV	
OUTER NORMAL BACKLASH	MIN 0.002"	MAX 0.004"
TOOTH TAPER	DPLX	
CUTTING METHOD		SR
GEAR TYPE		GENERATED
FACE WIDTH IN PERCENT OF CONE DISTANCE . .		26.011

	PINION	GEAR
GEOMETRY FACTOR-STRENGTH-J .	0.2215	0.2215
STRENGTH FACTOR-Q	36.158	36.153
SIZE FACTOR - KS	0.557	
FACTOR . . . . KI	1.3544	
STRENGTH BALANCE DESIRED . . STRS		
STRENGTH BALANCE OBTAINED . STRS		
GEOMETRY FACTOR-DURABILITY-I	0.0587	
DURABILITY FACTOR-Z	8219.	8219.
GEOMETRY FACTOR-SCORING-G .*	0.003523	
SCORING FACTOR - X	0.5007	
ROOT LINE FACE WIDTH	0.515"	0.515"
PROFILE SLIDING FACTOR . . .	0.002260	0.002260
RATIO OF INVOLUTE/OUTER CONE	2.313	

	PINION		GEAR
AXIAL FACTOR-DRIVER CW . . . OUT	0.211	OUT	0.211
AXIAL FACTOR-DRIVER CCW . . OUT	0.211	OUT	0.211
SEPARATING FACTOR-DRIVER CW SEP	0.211	SEP	0.211
SEPARATING FACTOR-DRIVER CCW SEP	0.211	SEP	0.211

DUPLEX SUM OF DEDENDUM ANG .
ROUGHING RADIAL . . . . 3.459"

*THIS FACTOR IS USED IN THE 1966 SCORING FORMULA

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APPENDIX C

NASA STATEMENT OF WORK

For convenient reference, relevant portions of the NASA Statement of Work for the Electromechanical Flight Control Actuator are presented in this appendix.

1.0 OBJECTIVES

The objectives of this Statement of Work (SOW) are as follows:

a. Conduct a thorough test and evaluation program of the redundant, four-channel, electromechanical actuator developed under NASA Contract NAS 9-14331.

b. Perform additional anaylsis and measurement tasks to resolve possible application problems.

c. Fully document the actuator design test and evaluation results and related analysis to be performed.

2.0 END ITEMS

The end items of this contractual effort shall be as follows:

a. EMA completed to a four-channel configuration, and associated hardware.

b. Test equipment and instrumentation residual from NAS 9-14331 or procured under the terms of this contractual effort.

c. Coded program tapes or computer card decks, listings, descriptions, and users instructions for those analytical models developed and used by the contractor under the terms of this contractual effort.

d. Documentation in accordance with the SOW and DRL (data requirements list).

3.0 TASK DESCRIPTION

The following defined tasks shall be completed under this SOW:

3.1 DESIGN, FABRICATION, AND MAINTENANCE

3.1.1 ELECTROMECHANICAL ACTUATOR (EMA)

The contractor shall perform those tasks necessary to complete the fabrication of the EMA to a full four-channel configuration in accordance with the current design base plus any modification(s) required to complete the design verification tests delineated herein under SOW paragraph 3.3. The current design base is represented by the latest design status achieved under NASA Contract NAS 9-14331. The contractor shall perform normal maintenance and repair of the EMA as necessary to enable the accomplishment of all SOW tasks, within the limitations of the NASA-furnished test stand, the EMA, and associated equipment, and to deliver it at the end of this contract.

3.1.2 TEST EQUIPMENT AND INSTRUMENTATION

The contractor shall perform all test equipment and instrumentation design and fabrication tasks as necessary to satisfy the test objectives of this SOW. The contractor shall maintain and repair all such equipment as necessary to complete the test objectives of this SOW.

3.1.3 NASA EMA TEST STAND

The contractor shall provide for modification to and maintenance and repair of the NASA furnished test stand as necessary to complete the test objectives of this SOW.

3.2 ANALYSIS

3.2.1 EMA ANALYTICAL MODEL DEVELOPMENT

The contractor shall perform those tasks necessary to develop analytical models of the EMA system and its simulated loads. Modeling shall include all major blocks such as the current source, power conditioner, motor, gearbox, tachometer, rotor position sensor, position sensor, and control electronics. System models shall be provided for analyzing steady state and transient conditions under various load conditions, linearized frequency response characteristics, and all major nonlinear effects such as hysteresis, torque limiting, and velocity limiting. The contractor shall establish the validity of the analytical models by establishing the correlation of analytical results with hardware test results (DVT, development, etc.) resolving any significant differences in steady state and/or transient performance.

The contractor shall utilize analytical results and hardware test results as necessary to optimize EMA systems gains and compensation to achieve the best possible system performance.

3.2.2 POWER SWITCH EVALUATION

The contractor shall analyze and evaluate the operating modes of all power components to establish their design margins. Actual measurements of the transient voltage and current profiles shall be made for all switch components in all operating modes. The compatibility of the electrical dynamics of the switch with the component ratings shall be explained. When inadequacies are found in the present designs, recommendations shall be made regarding methods to be used to provide safe operating regimes for all power components. Critical analysis and/or experiments shall be conducted where feasible, to verify that the proposed approach is adequate.

The contractor shall also provide an alternate design approach to the present power switching mechanization which would permit switch components to operate at low stress levels. A preliminary design and anaylsis of this approach shall be accomplished and documented.

The contractor shall submit a task plan for approval by the NASA technical monitor at least 30 days prior to start of this effort. The task plan shall be prepared to the requirements of DRL Item No. 3.

3.2.3 POWER ELECTRONICS BREADBOARD

The contractor shall perform the following work relative to the power electronics:

a. The contractor shall establish power switching requirements for the power components when driving the motor in each of 4 quadrants as required in figures 1, 2, and 3.

b. The contractor shall identify worst case operating conditions for the power component.

c. The contractor shall identify and specify minimum power component characteristics required for safe (reliable) operations under worst case conditions.

d. The contractor shall evaluate the characteristics of available power components (transistors, etc.) against required characteristics and established design margins and identify those cases where the ratings of presently available components are equal to or exceed said requirements and margins. The contractor shall evaluate components from two or more suppliers. The contractor shall evaluate the NASA-furnished power transistor (currently being developed by Westinghouse under the terms of Contract NAS 3-18916) and should consider the Power Tech Transistor PT-3523.

e. The contractor shall test the NASA-furnished power transistor and shall procure samples of power components with specifications adequate for the established requirments and design margins. The contractor shall test these components in circuitry which duplicates worst case conditions as determined in 3.2.3.b. The contractor shall establish power component design margins under these conditions. The contractor shall determine those power transistor parameters most critical to the identified switching requirements. The contractor shall recommend preferred power transistor parameters for each power switching application.

f. The contractor shall recommend a preferred power electronics design. The recommended design shall be submitted to the NASA technical monitor for review and approval. Power components determined to be most promising from 3.2.3.d and 3.2.3.e shall be incorporated in the recommended design.

The contractor shall fabricate the approved power electronics design. The contractor shall conduct tests of the power electronics against those design margins determined to be adequate in 3.2.3.e above. If, in the judgment of the contractor, it is not feasible to achieve adequate design and/or performance margins on the component and system levels, the contractor shall identify and analyze componert and/or design inadequacies and recommend alternate components and/or design approaches that provide adequate design margins.

The contractor shall submit a task plan for approval of the NASA technical monitor at least 30 days prior to start of this effort. The task plan shall be prepared to the requirements of DRL Item No. 3.

The contractor shall submit a report on the evaluation, test and breadboard performance of the power components. The report shall be prepared to the requirements of DRL Item No. 4.

3.2.4 ANALYTICAL RESULTS

The contractor shall provide interim results of all analysis tasks to the NASA technical monitor on an informal basis. The contractor shall thoroughly document all analyses in a final report.

3.3 DESIGN VERIFICATION TEST

3.3.1 GENERAL

The contractor shall subject the EMA to design verification tests in accordance with this section to demonstrate compliance with this Statement of Work.

3.3.2 ELECTRICAL POWER

The contractor shall provide the electrical power for these tests at a nominal 270 vdc voltage level.

3.3.3 TEST EQUIPMENT

3.3.3.1 NASA EMA TEST STAND

The contractor shall utilize the NASA EMA test stand to load the EMA within the design limits of the test stand. The contractor shall measure the clevis arm displacement from the neutral (no load) position.

3.3.3.2 DELTA TEST EQUIPMENT AND INSTRUMENTATION

The contractor shall determine test equipment and instrumentation requirements in addition to that furnished from NAS 9-14331 which

are necessary to accomplish the test objectives of this SOW. Instrumentation shall include gearbox torque transducers. The contractor shall consider the need for position transducers to measure for load deflection, temperature sensors, and power measurement instrumentation. The contractor shall provide all acquisition and installation of additionally required test equipment and instrumentation.

3.3.4 PERFORMANCE TESTS

Many of the EMA performance requirements given in this section are expressed in terms of percentage levels based on 55 degrees full-stroke displacement of the output rotary actuator(s) for all combinations of two motors operating. The displacement levels are expressed in terms of % FT (full travel). Hereinafter, 100% FT shall represent the 55 degrees of full-stroke displacement.

The contractor shall evaluate all of the actuator performance or design specifications defined in the SOW for NAS 9-14331 as applicable against the design baseline established in section 3.1.1. As a minimum, the contractor shall test to or against all specifications identified in subsequent paragraphs of this section. It is recognized that this is a test program and that all specifications represent design goals only. Where specifications include "all combinations of any two channels," detailed test of any two channels substantiative as typical is acceptable.

3.3.4.1 OUTPUT STROKE

With any single or combination of any two channels operating, the EMA shall be capable of positioning the output over the entire stroke; i.e., 55 degrees (+15, -40 degrees).

3.3.4.2 OUTPUT VELOCITY

For all combinations of any two channels operating at no load, the EMA shall provide maximum open loop (open position loop only) velocity of 21 degrees/second. Minimum velocity requirements under loaded conditions are specified in figure 1.

3.3.4.3 OUTPUT TORQUE

The EMA, for all combinations of any two channels operating together in either direction of rotation, shall be capable of the dynamic response as specified in figure 1.

3.3.4.4 DISPLACEMENT LINEARITY

For all combinations of any two channels operating, displacement linearity, defined as the relationship between the input position command signal and the output position as measured by the output position transducer, shall be linear within 1% FT.

3.3.4.5 THRESHOLD

For all combinations of any two channels operating at no load, threshold, defined as the largest sinusoidal input amplitude that may be applied at 0.01 Hz without producing output motion, shall not exceed 0.05% FT of the input signal required to achieve 100% FT.

3.3.4.6 POSITION NULL

With the input signal at zero, for all combinations of any two channels operating at no load and the position offset controls set at zero, the output position of the EMA measured from its neutral position shall not exceed 0.5% FT. The position offset control of any channel shall be capable of displacing the neutral position of the output clevis an amount equivalent to ±5% FT.

3.3.4.7 HYSTERESIS

For all combinations of any two channels operating, hysteresis, defined as the maximum difference between output positions obtained when traveling clockwise then counterclockwise during a 0.01 Hz sinusoidal input with an amplitude of 50% FT, shall not exceed 0.05% FT.

3.3.4.8 CROSS-CHANNEL VELOCITY TRACKING

The steady-state angular velocity difference between any combination of motors operating shall not exceed 3% of maximum motor velocity, for any command signal within the operating range applied equally to all channels.

3.3.4.9 FREQUENCY RESPONSE

The EMA, for all combinations of two channels operating, shall be tested closed loop to demonstrate compliance with figure 2. The input amplitude shall theoretically give +0.5% FT at 0.1 Hz. The amplitude ratio, output peak-to-peak displacement achieved divided by 1% FT, expressed in decibels and phase shift, expressed in degrees, shall fall within the envelope shown in figure 2.

3.3.4.10 STEP RESPONSE

Tests, for all combinations of two channels operating, shall be performed to demonstrate compliance with requirements of figure 3.

3.3.4.11 MOTOR BRAKE

Each brake shall brake a de-energized motor from full speed to zero speed while holding against that torque required to drive the maximum load. No electrical power shall be rquired to engage the brake (brake motor).

3.3.4.12 CHATTER AND INSTABILITY

The EMA shall operate smoothy without instability excessive chatter or excessive noise under all conditions specified herein. Limit cycling for any channel under no load and steady-state command conditions shall exceed 0.055 degrees peak-to-peak.

3.3.4.13 VELOCITY GAIN TEST

The contractor shall perform tests to determine no-load, open position-loop velocity gain characteristics for each channel separately and for all combinations of any two channels.

3.3.4.14 TORQUE GAIN TEST

The contractor shall perform tests to determine open-position-loop torque gain characteristics for each channel separately and for all combinations of any two channels.

3.3.5 TEST PLAN

The contractor shall submit a detailed test plan for approval by the NASA technical monitor at least 30 days prior to the start of testing. The test plan shall be prepared to the requirements of DRL item no. 5.

4.0 <u>PROGRAM REQUIREMENTS</u>

4.1 CONFERENCE REQUIREMENTS

The contractor shall support formal reviews. These reviews shall be chaired by NASA JSC, and the contractor shall prepare and make available to the attendees all documentation necessary to accomplish the objective of the review. One (1) review shall be conducted at the Johnson Space Center; two (2) reviews shall be conducted at the contractor's facility at Goleta, California.

4.2 DOCUMENTATION REQUIREMENTS

The contractor shall furnish all data items identified and described on the DRL (data requirements list), JSC Form 2323. The data items

shall be prepared in accordance with the DRD (data requirements description), NASA Form 9, and JSC Form 2341, attached to the DRL and referenced on the DRL for each line of data specified thereon. Where practical, the contractor's own internal documents shall be utilized to meet and/or supplement the requirements specified in the applicable DRD. Internal documents need not be retyped or reprinted prior to submission.

Attachment 1 is a completed DRL with associated DRD's applicable to this Statement of Work.

EM ACTUATOR DYNAMIC RESPONSE REQUIREMENTS

CONDITION I	DR (%)	TIME (MIN)	RATE (DEG/SEC)	EM (IN-LB x 10
STEADY STATE LIMIT CYCLE (2.5[4] Hz @ 1° PP)	- 100	- 26	10 5 (Avg)	.495[1] .300[2]
CONDITION II				
STEADY STATE LIMIT CYCLE (1 Hz @ 4° PP)	- 100	- 5.5	15 8 (Avg)	.495[3] .140 (Avg
CONDITION III				
STEADY STATE LIMIT CYCLE	- 100	- 1.5	20 8 (Avg)	.357 .140 (Avg
CONDITION IV	100	5	0	.495

DESIGN GOALS:

(1) $.518 \times 10^6$ IN-LB

(2) $.455 \times 10^6$ IN-LB

(3) $.539 \times 10^6$ IN-LB

(4) .3 Hz @ 1°PP

FIGURE 1

EM ACTUATOR FREQUENCY RESPONSE
(AMPLITUDE RATIO)

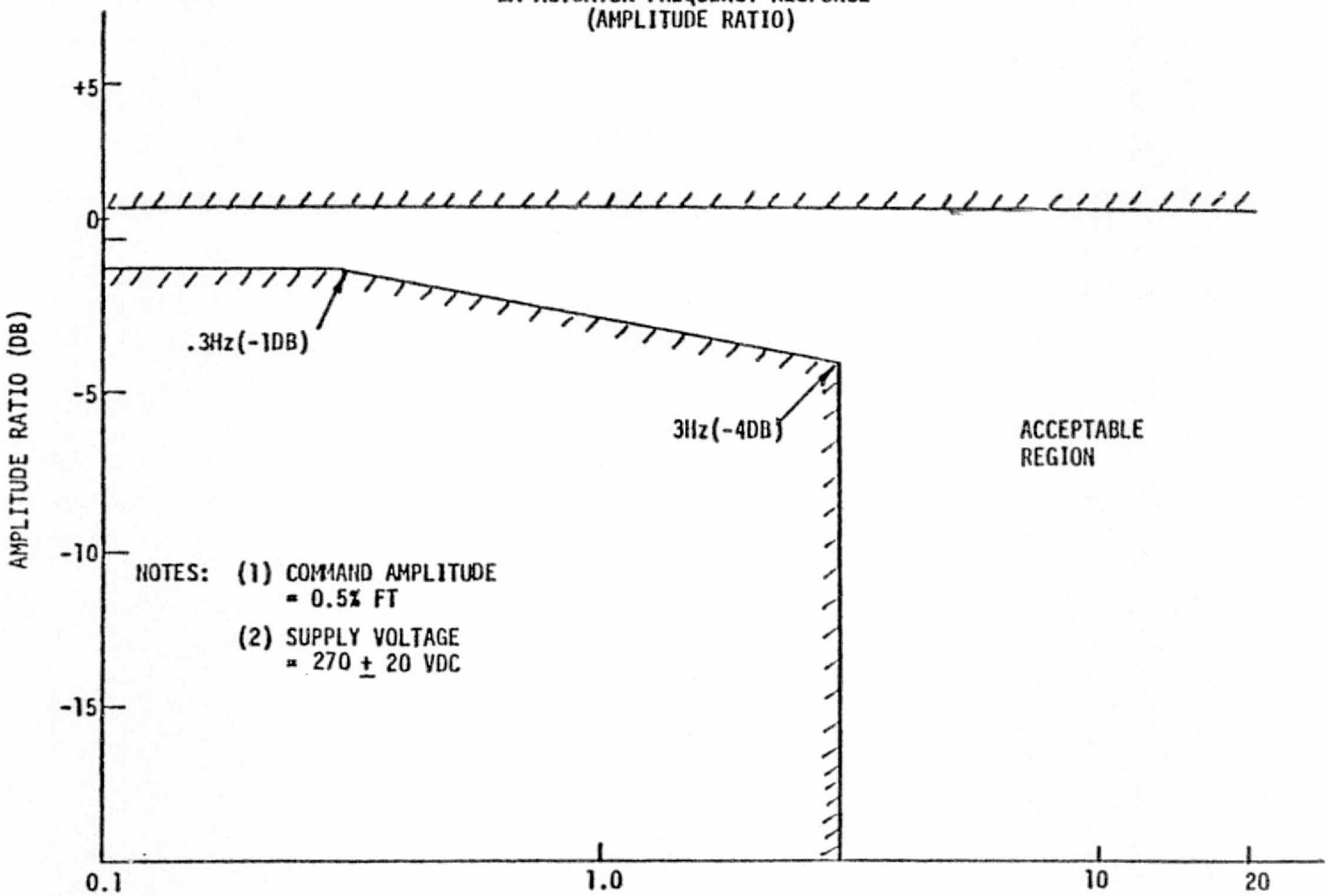

FIGURE 2

EM ACTUATOR FREQUENCY RESPONSE
(PHASE SHIFT)

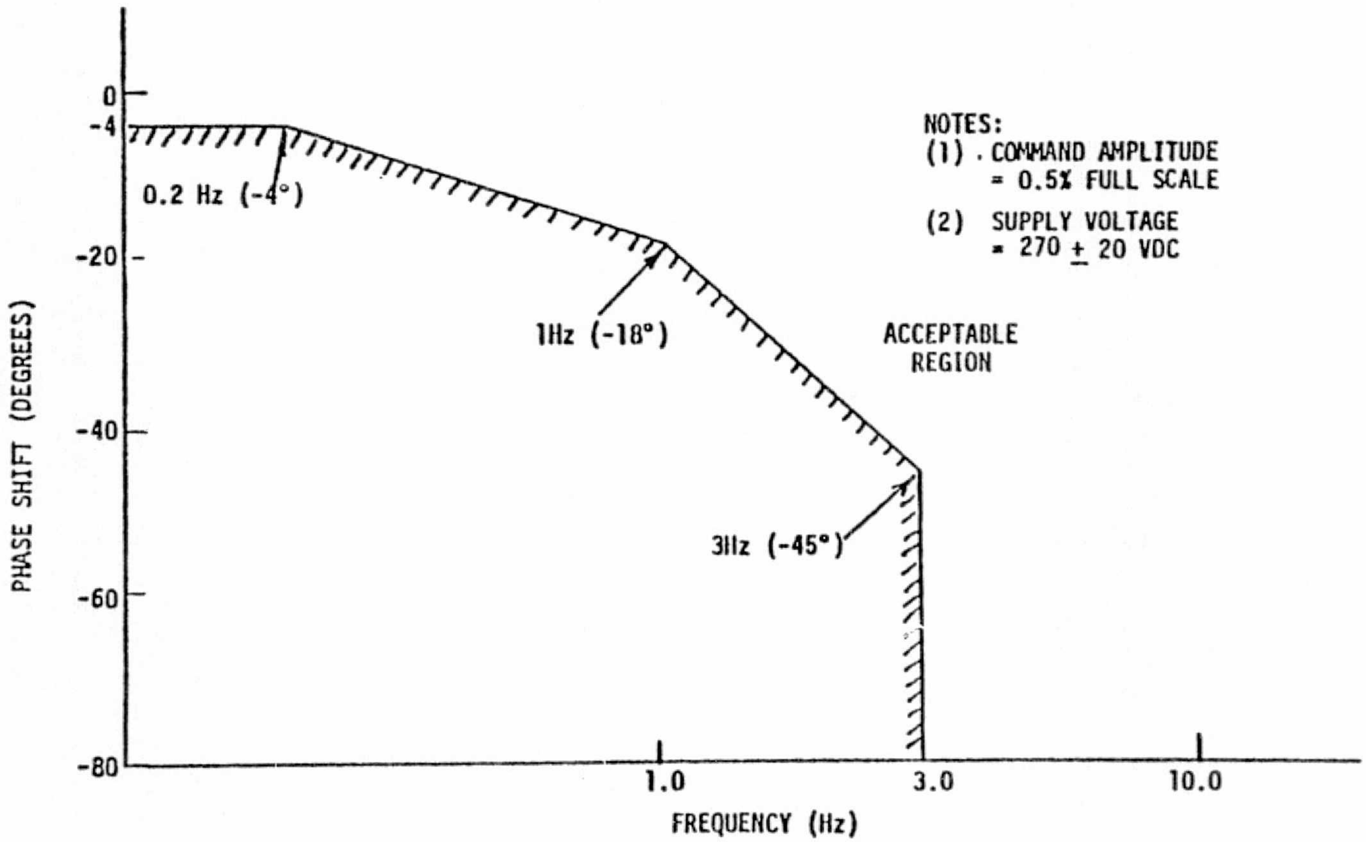

FIGURE 2a

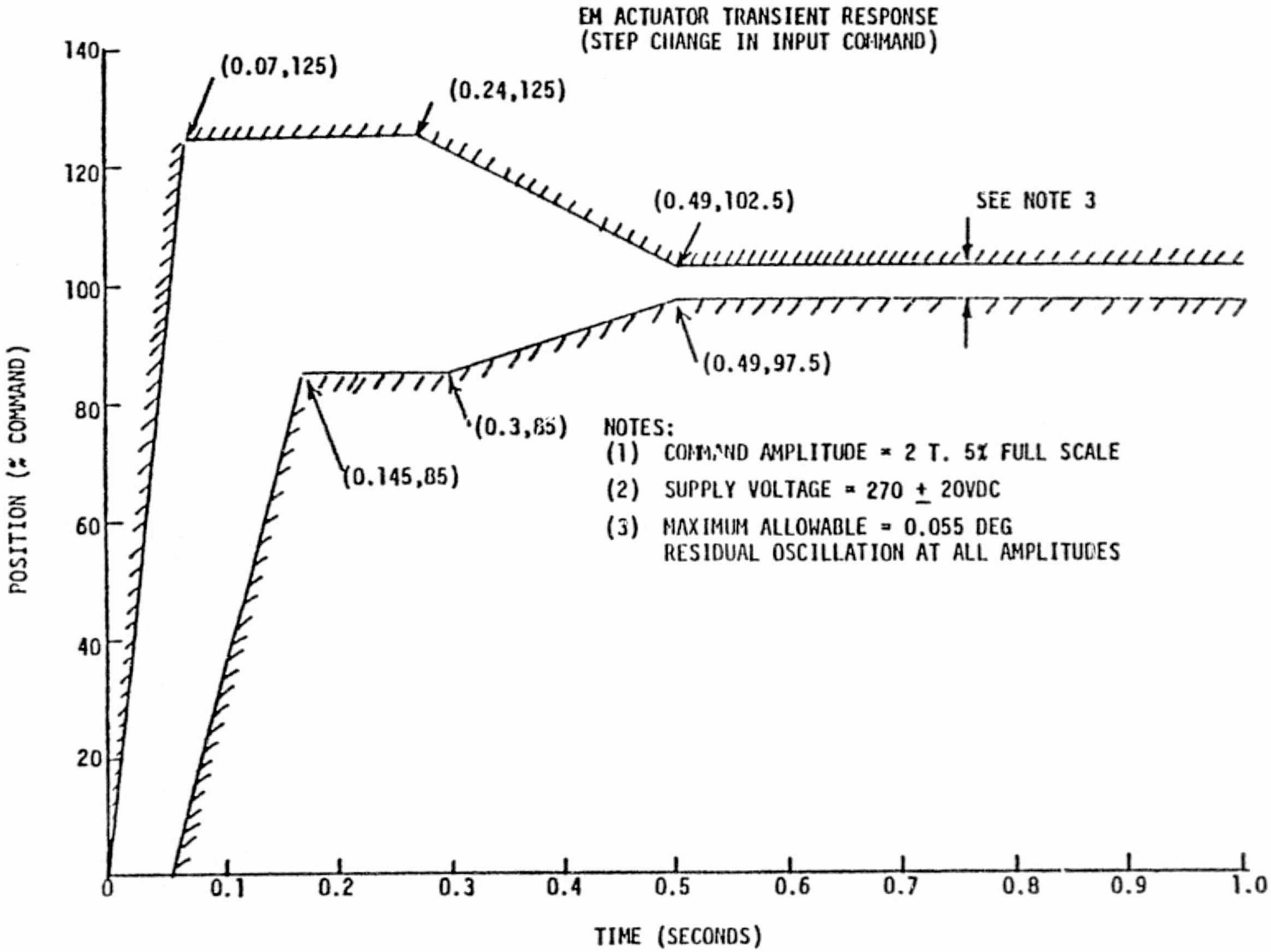
EM ACTUATOR TRANSIENT RESPONSE
(STEP CHANGE IN INPUT COMMAND)
140
120
100
80
60
40
20
POSITION (% COMMAND)
(0.07,125)
(0.24,125)
(0.49,102.5)
SEE NOTE 3
(0.49,97.5)
(0.145,85)
(0.3,85)
NOTES:
(1) COMMAND AMPLITUDE = 2 T. 5% FULL SCALE
(2) SUPPLY VOLTAGE = 270 ± 20VDC
(3) MAXIMUM ALLOWABLE = 0.055 DEG
RESIDUAL OSCILLATION AT ALL AMPLITUDES
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
TIME (SECONDS)

FIGURE 3

APPENDIX D

OPERATIONS MANUAL

For convenient reference, the Operations Manual for the Electromechanical Actuator is reproduced in this appendix.

28 OCTOBER 1977

OPERATIONS MANUAL

for the

ELECTROMECHANICAL ACTUATOR

CONTRACT NAS 9-14952
DRL Item 2

Submitted to
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
L. B. Johnson Space Center
Houston, Texas

Delco Electronics

General Motors Corporation
- Santa Barbara Operations
Santa Barbara, California

TABLE OF CONTENTS

INTRODUCTION

The electromechanical actuator (EMA) system consists of an electronics rack (figure 1), a test stand assembly (figure 2), and interconnecting power and signal cables. The electronics rack houses the power electronics (which control the motor and brake currents), the low-level control circuitry, and the necessary power supplies, contactors, relays, controls, displays and other related equipment used to power and control the actuator. Electrical power (both 115 Vac and 270 Vdc) is supplied to the electronics rack.

The test stand assembly includes the four EMA motors, the differential gearbox which sums the output velocities of the motors, planetary gear reducers which are driven by the differential gearbox output shaft, load springs, and the linkages which connect the load springs to the planetary gear reducers. This assembly also has terminals for electrical cables, a receptacle for a compressed air hose, an air filter, and a manifold and air hoses which distribute cooling air to the four EMA motors. Torque transducers are provided to measure the torques transmitted by the differential gearbox output shaft, and linear potentiometers (to sense load motion) are also mounted on the test stand assembly.

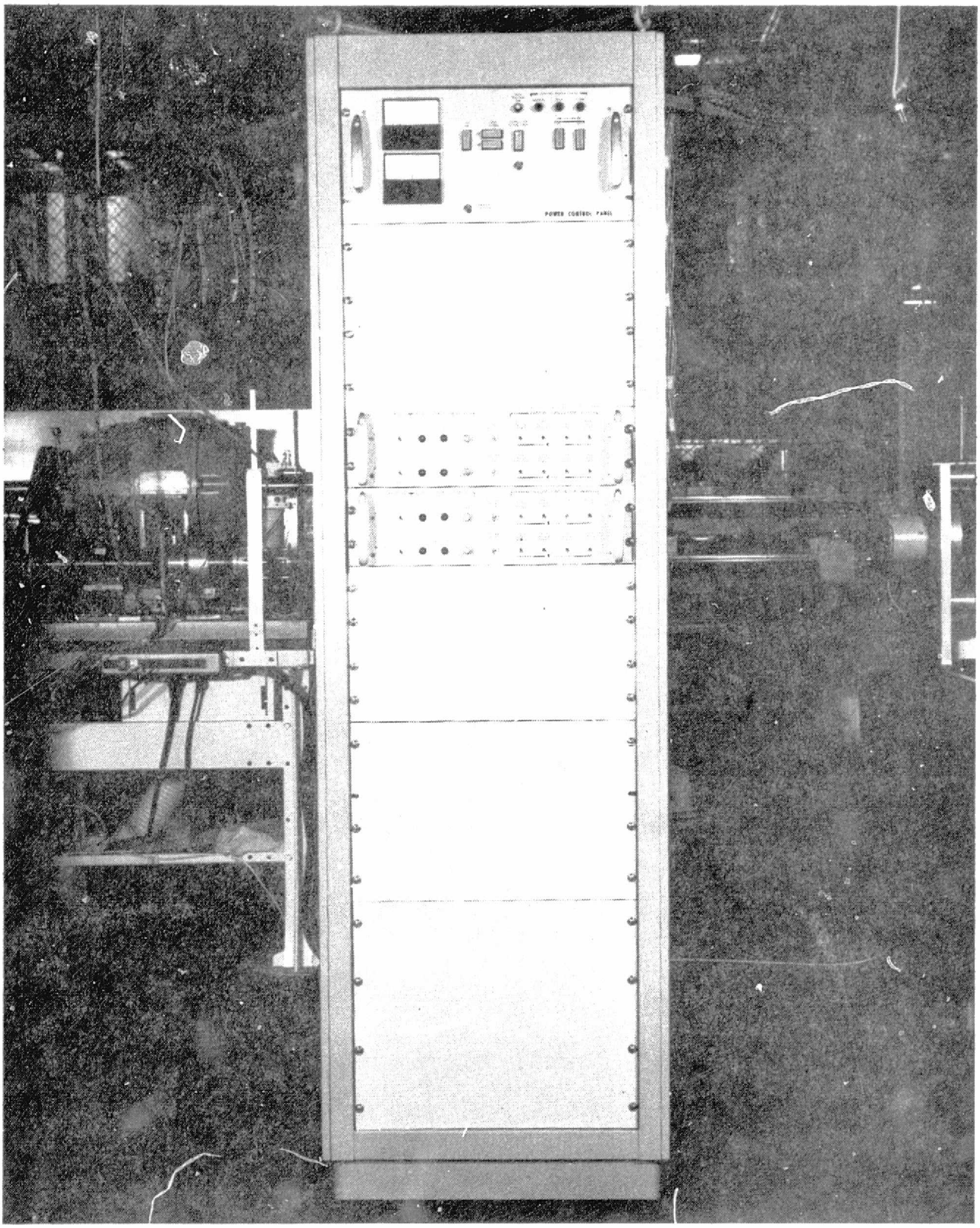

Figure 1. Electronics Rack

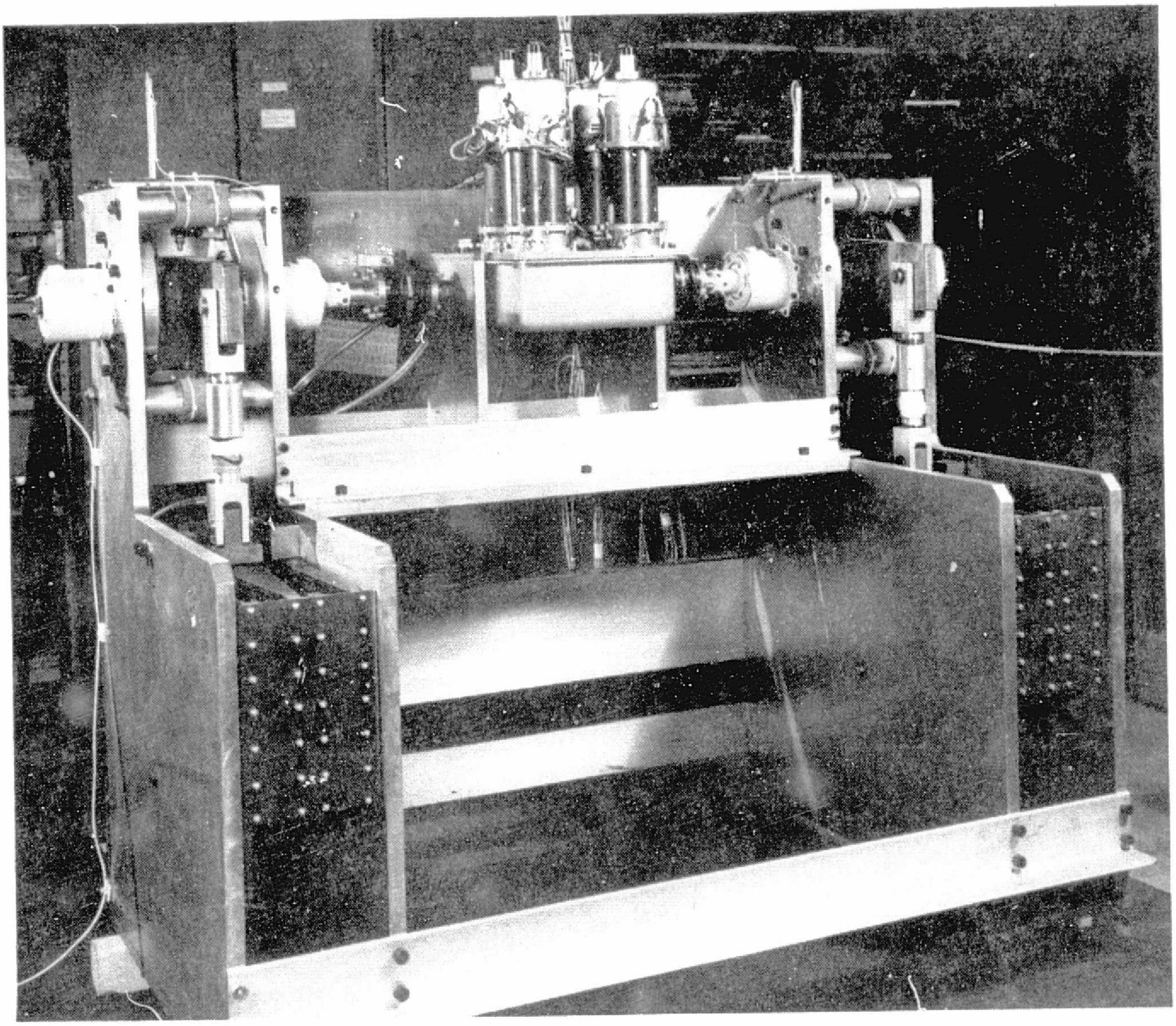

Figure 2. Test Stand Assembly

SAFETY CONSIDERATIONS

All persons operating or working in the vicinity of the EMA should be well-acquainted with the hazards associated with high power electronic and mechanical equipment. The voltages and currents are large and potentially dangerous. The load springs and battery store large amounts of energy and are also very hazardous.

All reasonable precautions should be taken in setting up facilities for the EMA. Persons not familiar with the equipment should be prevented from entering dangerous areas. Adequate grounding, fused circuits and high-voltage matting should be provided. The batteries which furnish the nominal 270 Vdc power should be adequately ventilated and protected from accidental shorts. Cabling should be protected, and necessary fencing or other constraints should be used to keep personnel away from dangerous voltages, rotating equipment, springs or batteries. Warning signs should be provided for all dangerous areas. No one should work on this equipment alone. Personnel who work on the equipment should be very familiar with the life-saving techniques (such as mouth-to-mouth resuscitation) which may be required for electrical shock victims.

Battery servicing and maintenance (including filling and charging) should be accomplished by experienced personnel in accordance with the battery manufacturer's recommendations.

Clear access to power switchgear, fire extinguishers and exits should be maintained at all times. Test equipment, work tables or other similar equipment should be placed in locations which do not interfere with equipment operation nor limit access to exits or safety-related equipment.

Whenever it is necessary for personnel to be close to the power electronics or load stand, all input power to the EMA should be disconnected. In addition, the energy storage capacitors should be discharged. Bleed resistors automatically provide for capacitor discharge, but require several minutes to reach safe voltage levels. A switch located on the upper panel of the electronics rack (see figure 3) provides much faster capacitor discharge when pressed. The voltmeter at the upper left corner of the Power Control Panel displays the voltage across the energy storage capacitors. As an added precaution after removing electrical power, the ac circuit breaker (located on the bottom rear panel of the electronics rack) should be opened.

The 115 Vac power which is supplied to the equipment should be of good commercial quality, and the battery bank should provide 270 Vdc nominally. The dc voltage should never be allowed to exceed 325 Volts under any conditions, since higher voltages could damage the power electronics. Appropriate voltage limiting circuits must be provided on the battery

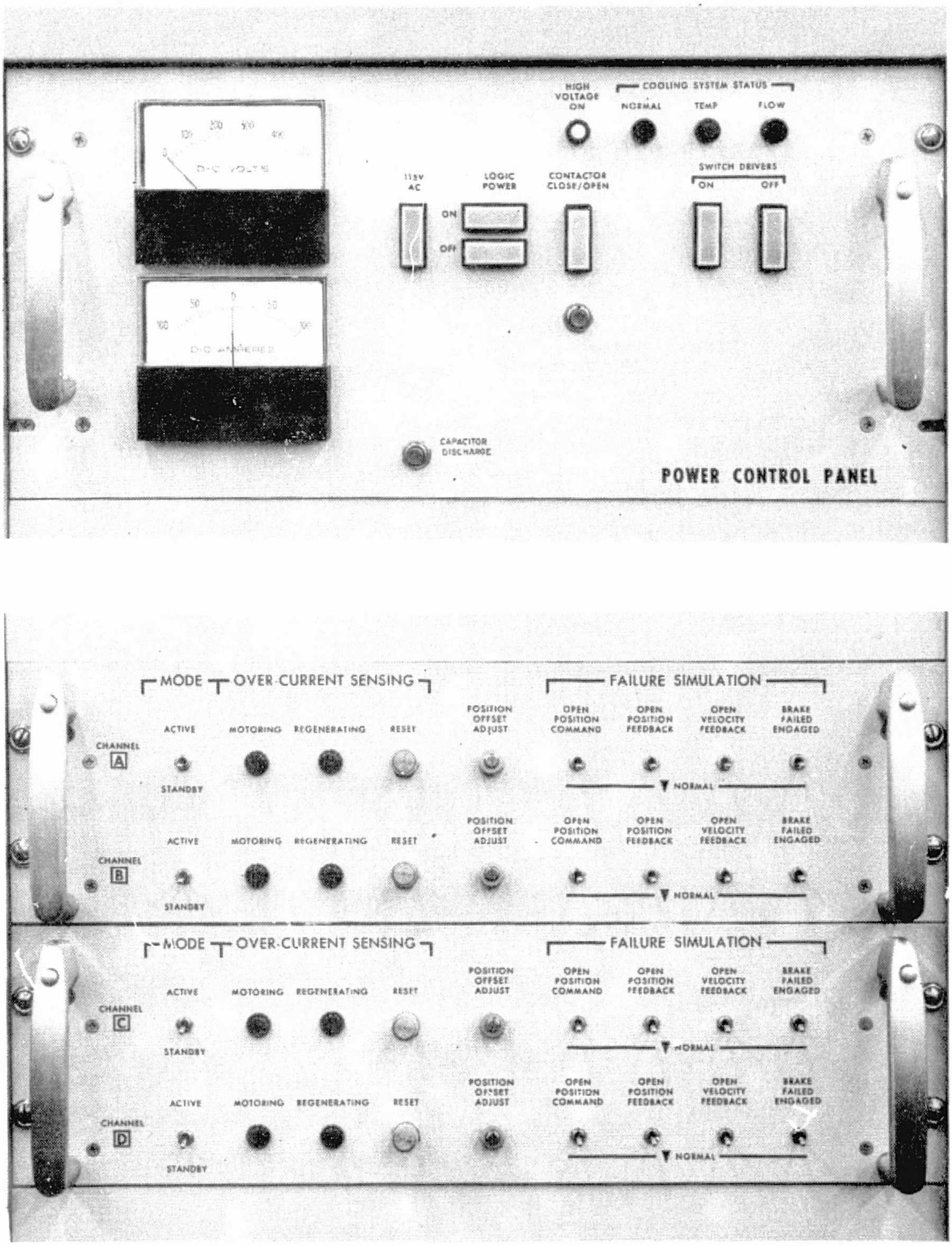

Figure 3. Electronics Rack Panels

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charger so that it cannot supply excessive voltage under any condition (including inadvertent operation without battery bank connected to the EMA).

Although operating the EMA is very simple, it must be recognized that large amounts of power and energy are involved, and it is therefore essential that all personnel involved in EMA operations or maintenance use great care to make sure no unsafe conditions ever exist.

During tests, it is recommended that buffered signals (from area A of the low-level electronics drawer) be used for display or recording purposes. If direct access to other signals is necessary, it is recommended that the load springs be disconnected. In addition, the operator should use great care to minimize the possibility of inadvertent shorts or disturbances that might cause excessive motor currents or other dangerous conditions. If circuit modifications have been made, such as opening the various control loops, the load springs should be disconnected while checking out EMA operation. Before re-connecting the load springs, the EMA should be checked to ensure that it is operating properly. In addition it must be at its neutral position when the load springs are re-connected; otherwise only the limit switches on the load stand would prevent the load (clevis) arms from hitting the stand.

As part of the EMA operations, all equipment should be periodically examined for loose parts, adequate clearances and other mechanical or electrical problems. Unusual noises or other indications of erratic operation should be immediately investigated.

START-UP OPERATIONS

Cooling Air

Before start-up is initiated, cooling air for the EMA motors should be turned on by opening the cooling air control valves. It is good practice to make sure that air is flowing out of each of the four EMA motors before turning on electrical power.

Input Command Signal

The EMA input command signal is introduced through a BNC connector (labelled P1) located on the rear of the power control drawer (the top drawer in the electronics rack). The signal is scaled to provide one degree of EMA load motion for each volt of input command signal. The EMA load motion is limited to ± 10 degrees, hence the input command voltage range is ± 10 volts. However, input signals of ± 20 volts will not cause any damage to the equipment. Prior to start-up, it is good practice to set the input command at zero volts.

Turn-on

Ac power for the electronics equipment is brought in through a circuit breaker located at the bottom rear of the rack. The circuit breaker switch must be on to allow EMA operation.

To initiate turn-on, the 115V AC power switch on the POWER CONTROL PANEL (figure 3) is pressed. Logic power (and other low-level power) is turned on by pressing the LOGIC POWER ON switch. For a few seconds after this switch is pressed, an audible alarm will sound. This is a normal part of the start-up cycle, and indicates that the protection circuitry is being re-set and is operational. The next switch in the start-up sequence should not be pressed until the audible alarm has stopped sounding. During normal operation the audible alarm will sound if an overcurrent condition is detected in any motor. A momentary overload will cause the appropriate indicator (located on the low-level control electronics drawer) to be illuminated. This will indicate which EMA channel has the overcurrent, and the indicator will also show whether the overcurrent occurred in a motoring mode or a regenerating mode. If the audible alarm should sound during operation, the EMA should be shut down, and the cause of the overcurrent should be determined.

In the normal start-up sequence, after the audible alarm has stopped sounding, the rectangular CONTACTOR CLOSE/OPEN switch is pressed. This causes 270 Vdc to be applied to the system. The battery voltage (as it appears across the energy storage capacitors) will be displayed on the voltmeter located on the upper left section of the POWER CONTROL PANEL.

If the dc supply voltage is satisfactory (approximately 270 Vdc), the channels which are to be activated are selected by placing the ACTIVE/STANDBY switch for each channel (located

at the left end of the front panel on the low-level electronics drawer) in the appropriate position. Normally, two channels will be in the active mode, and two will be in the standby mode. Drive power for the motors is initiated by pressing the SWITCH DRIVERS ON switch (located on the POWER CONTROL PANEL). The EMA is then ready for operation and will respond to the input command signal which may now be applied.

EMA OPERATING MODE

After the start-up sequence has been completed, the input signal may be varied to cause the EMA to drive its load. It is recommended that the system to be shut down if any circuit changes are to be made or if the load springs are to be connected (or disconnected).

If tests on the low-level circuits are to be made, it is not necessary (nor desirable) to go through the entire start-up sequence. After the logic power has been turned on, the low-level circuits can be operated without requiring any additional steps in the start-up sequence.

If the overcurrent sensor should ever be activated during EMA operations, the audible alarm will sound and the appropriate indicator will be illuminated. If this should occur, it is recommended that the system be shut down, and the cause of the alarm be determined.

SHUT-DOWN OPERATIONS

When the system is to be shut down, the input command should be set to zero. This will return the EMA to its null position and thus bring the load springs back to their neutral condition. This removes the hazards associated with leaving the load springs in a deflected position. At this point it is good practice to place all channels in the standby mode (this causes the brakes to be engaged and prevents the motors from being driven). The SWITCH DRIVER OFF switch is then pressed (removing the motor drive currents). Next, the red button under the CONTACTOR CLOSE/OPEN switch is pressed. This opens the dc contactor, removing the connection between the battery and the energy storage capacitors. However, as discussed earlier, the bleed resistors provide a rather slow discharge of the capacitor bank, and dangerous voltage levels will be present (as indicated on the POWER CONTROL PANEL voltmeter) for several minutes. If it is necessary to shorten this time, the CAPACITOR DISCHARGE switch (located on the POWER CONTROL PANEL) may be pressed. The LOGIC POWER OFF switch is next pressed to turn off the low-level power supplies (it is not necessary to discharge the capacitors before turning off logic power). The 115 VAC switch is then pressed to turn off the ac power.

Removing the input command signal and shutting off the cooling air valves complete the shut-down sequence.

APPENDIX E

MOTOR TESTS

This appendix contains Delco document EE-22-R-EMA-011 which covers tests conducted on the EMA motor and its current source inductor.

TITLE: ELECTROMECHANICAL ACTUATOR MOTOR AND INDUCTOR TESTS

BY: A.H. Barrett

APPROVED:

DATE: 8-20-77

CONTENTS

TITLE: EM Actuator Motor and Inductor Tests

BY: A. H. Barrett

APPROVED:

DATE: 6/28/77

I. INTRODUCTION

Tests were performed on two typical PM electromechanical actuator motors. The fully assembled motor used in all tests, except those involving a stator only, was Delco Part No. DL-00746, Serial No. 5. For stator only tests, Serial No. 6 (without a rotor) was used.

In general, the purpose of these tests was to acquire accurate quantitative data which may be used for verification of design and for development of a model. It is believed that these data, when used in conjunction with certain physical specifications which may be obtained from other reports, should give ample information for detailed analysis. Little analysis is included here, however.

These motors meet or exceed all their design requirements as these tests indicate. Excellent electromechanical actuator performance can certainly be anticipated.

II. TESTS AND SUMMARY OF RESULTS

A. DC Winding Resistance

The resistance of each phase to neutral was measured with a Leeds and Northrup Model 4288 Kelvin sensing bridge. The windings were at 25°C and the resistance of the brass connecting studs was not included. The observed results are as follows:

Line A to Neutral - 59.3 milliohm
Line B to Neutral - 59.7 milliohm
Line C to Neutral - 59.9 milliohm

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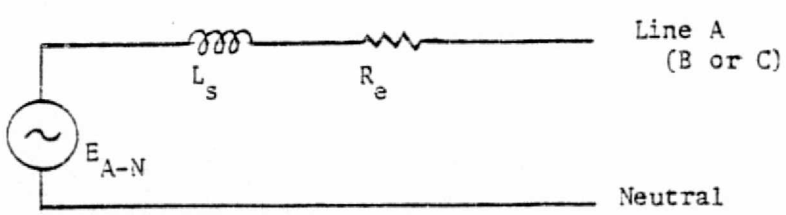
B. Equivalent Resistance

Equivalent resistance is, in this discussion, the resistance R_e in the Thevenin equivalent circuit for the motor shown below.



Thus it may be seen that R_e includes the DC resistance discussed above, plus another component R_{ac}, so that

$$R_e = R_{dc} + R_{ac}.$$

R_{ac} is used to account for all losses in the machine which exceed those which would occur for R_{dc} alone.

Contributing effects are thus as follows:

- Stator iron losses
- Proximity effects of windings
- Skin effects in the windings
- Rotor losses (generally negligible in this machine)

R_e was measured by three different methods. In the first method, mechanical power used to drive a short circuted alternator is equated to the power lost in heating the R_e of all of the three phases. Refer to Figure 1 for the test set up. The results appear in Table 1. (All figures and tables are presented in Appendix A).

In the second method, mechanical power, used to drive an alternator loaded with resistive loads, is equated to the sum of the power delivered by the alternator and the power lost in heating the R_e of all of the three phases. Refer to Figure 2 for the test set up.

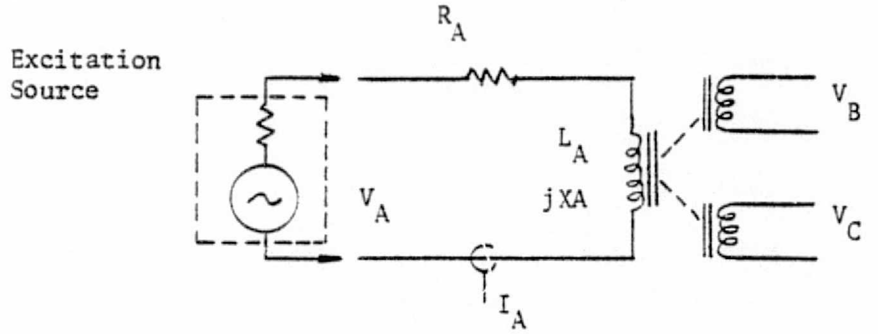
Note that the stator flux in the machine was higher than it was by the first method. Thus R_e may be expected to be somewhat higher by this method. See Table 2.

For the third method, R_e is equated with the R_a which is as calculated for 60 Hz and 400 Hz excitation of a single phase (line A to neutral). The calculated results are presented in Table 3. Note that R_a is a function of rotor position δ_e and increases, reflecting higher loss when the rotor position is such that there is greater induction in the unexcited phase poles. These data are plotted in Figure 3.

C. Winding Self-inductance

D. Winding Mutual Inductance

Winding inductances were measured as a function of rotor position, excitation current, and excitation frequency. The following discussion involves several variables which are defined in Table 4. The equivalent circuit for a stalled motor is assumed to be as shown.



The following measurements were taken - I_A, V_A, θ_A, V_B, and V_C. The self and mutual inductances were calculated using the following procedure.

$$V_A = (R_A + jX_A) I_A$$

$$V_{RA} = (\cos \theta_A) V_A$$

$$R_A = V_{RA}/I_A$$

$$V_{XA} = (\sin \theta_A) V_A$$

E. Winding Inductance, Incremental with DC Bias

These tests were conducted to determine the effect of direct current bias on winding inductance. The line to line inductance so measured is approximately that component which is seen by the controlled current source in EMA operation. The approximation is expected to be more accurate at low motor speeds. For these tests a small 4KHz perturbation is introduced on the constant MMF set up in the stator by a constant direct current source. 4KHz was chosen because it is the approximate modulation frequency used in the hysteresis controlled constant current source in the 4 channel EMA; also, calculations are simplified because winding impedance is almost purely inductive.

The circuit used for these tests is shown in Figure 4. Note that the AC perturbation source and the DC source are effectively paralleled across the winding under test. Interaction was avoided by using 2200 μF DC blocking capacitor for the AC source and a 60 mH air core AC

blocking inductor for the DC source. Excitation waveform was an excellent sinusoid and the 60 mH inductor, which was effectively in parallel with the winding under test was shown to cause less than 1% error in measured winding inductance in all cases.

Four series of tests were conducted. These tests whose results appear in Tables 6, 7, 8 and 9 were as follows:

- Line to neutral incremental inductance with $\delta_e = 0$
- Line to line incremental inductance with $\delta_e^* = 0$
- Line to neutral incremental inductance with rotor removed (mutuals calculated)
- Line to line incremental inductance with rotor removed

* $\delta e^* = 0$ means that the electrical torque angle for line to line DC excitation is zero (i.e. the rotor is in stable equilibrium).

For all of these tests the AC excitation was 2.0 A rms.

F. Current Source Inductor Incremental Inductance with DC Bias and DCR

An inductor is used in the controlled constant current source of the EMA direct power circuit. Its input voltage waveform is a nominal 4 KHz square wave. In normal operation the current waveform is ~~triangular~~ with a large value of DC offset. It is useful, therefore, to know its incremental inductance and DC resistance. The DCR was measured using a Leeds and Northrup Model 4288 Kelvin Sensing Bridge. At 25^{o}C, DCR equals 11.5 milliohms. Table 10 lists the results of incremental inductance measurements. The test circuit is shown in Figure 4. Note that the winding under test was this inductor, rather than the motor as shown.

For convenience the results presented in Tables 6, 7 and 10 are shown in curves plotted in Figure 5.

G. Open Circuit Voltage (or MMF) Waveforms

The motor was operated at several fixed speeds including rated speed on the Delco test bed. Open circuit terminal waveforms were recorded and various measurements made. The measurements are presented in Table 11.

Typical waveforms appear in Figures 6 through 14. Figure 15 is provided to demonstrate the excellent quadrantal (mechanical) symmetry.

H.. Cogging Torque

The term cogging is used to describe the tendency of the unexcited PM motor to seek particular rotor to stator relative positions which maximize stator flux. There are six such positions for each 360° of electrical rotation (i.e. twice the number of phases). These motors are 8 pole machines so that there are 24 positions of stable equilibrium for 360° of rotation.

The average value of cogging torque is approximately 1.5 in-lbs and the peak value is approximately 4 in.-lbs. A plot of cogging torque as a function of shaft position is given in Figure 16.

The cogging torque, it should be noted, appears to show hysteresis. It is believed that this is an artifact of the torque transducer and motor bearing. If this is true the actual average value of cogging torque is much closer to zero than 1.5 in.-lbs. and the actual peak value is probably less than 3 in.-lbs.

The set-up used to record cogging torque is presented in Figure 17.

I. DC Torque

For the DC torque tests the motor was excited from a constant current source driving either a single phase line to neutral or phase to phase. Torque versus electrical angle (equal to 4 times the mechanical angle) was plotted for several values of DC excitation current. The motor was rotated slowly by hand. The test set up is shown in Figure 17.

The peak values of torque for line to neutral and line to line excitation are presented in Table 12.

The plots of DC torque versus angular position are given in Figures 18, 19, 20, 21 and 22. The following are points worthy of note:

1. discontinuities are due primarily to backlash in the motor - torque transducer coupling
2. hysteresis is apparent (as with cogging torque) and is probably an artifact of the torque transducer and motor bearing drag.
3. the cogging component causes some apparent distortion (especially at low excitation levels) in the true DC torque waveform.

4. torque waveforms compare well with back electromotive force, or MMF, waveforms.
5. torque is essentially linearly related to excitation current.

J. Short Circuited Alternator Braking Tests

This test was performed to determine the effective winding resistance, with results presented in an earlier section, the maximum current in the alternator mode, and braking torque versus speed characteristics. The test set up is shown in Figure 1.

Data are shown in Table 13.

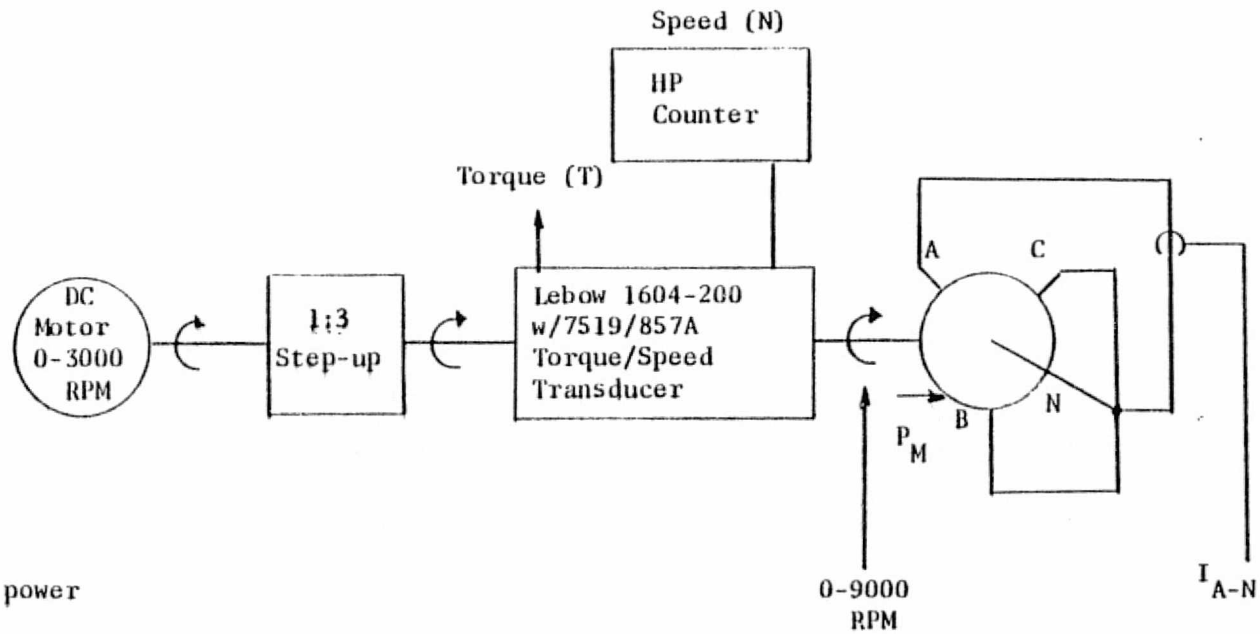
Plots of these data are provided in Figure 23 and Figure 24. Figures 25, 26, 27, and 28 show the waveforms recorded at selected points. Note that waveforms of all points are included in the Appendix.

K. Alternator Performance Under Load

The PM Motor was loaded line to neutral with a balanced 3 phase load. The load was adjusted to achieve several different rotor speed points at approximately one half and also full rated torque. The test set up and the equations are shown in Figure 2. The data of Table 14 are plotted in Figure 29.

APPENDIX A

Figures and Tables



P_M = KNT, P_M is mechanical power

$P_M \simeq P_D$, P_D is electrical power in watts

$P_D = 3\,(I_{A-N})^2 R_e$

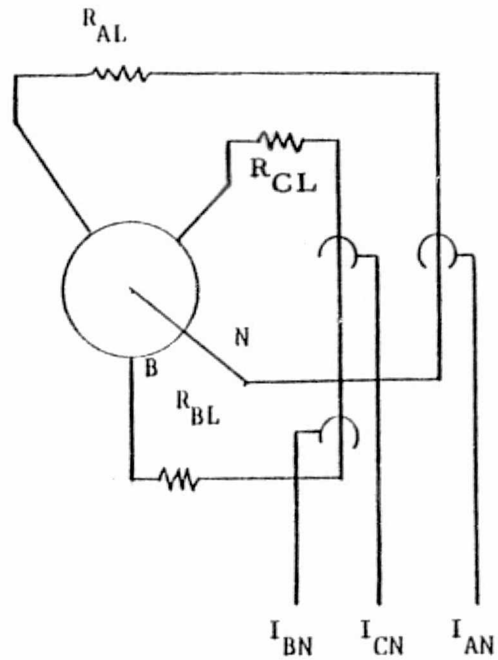
1 HP = 6600 in-lb per second = 745.7 watts

$P_D \simeq$ KNT (where $K = 11.83 \times 10^{-3}$, N = RPM, T = torque in in-lb.)

$R_e \simeq KNT/3I^2$ (where I is I_{A-N} in amperes RMS)

Figure 1 Short Circuit Testing

Same as Figure 1 -



$$P_M = KNT$$

$$P_M = P_{D\ Load} + P_{D\ Motor}$$

$$P_{D\ Load} = (I_{AN})^2 R_{AL} + (I_{BN})^2 R_{BL} + (I_{CN})^2 R_{CL}$$

$$P_{D\ Motor} \cong \left[(I_{AN})^2 + (I_{BN})^2 + (I_{CN})^2\right] R_e$$

$$R_e \cong \frac{KNT - (I_{AN} V_{AN}) - (I_{BN} V_{BN}) - (I_{CN} V_{CN})}{(I_{AN})^2 + (I_{BN})^2 + (I_{CN})^2}$$

$$R_e \cong \frac{P_M - P_{D\ Load}}{(I_{AN})^2 + (I_{BN})^2 + (I_{CN})^2}$$

Figure 2 Loaded Alternator Testing

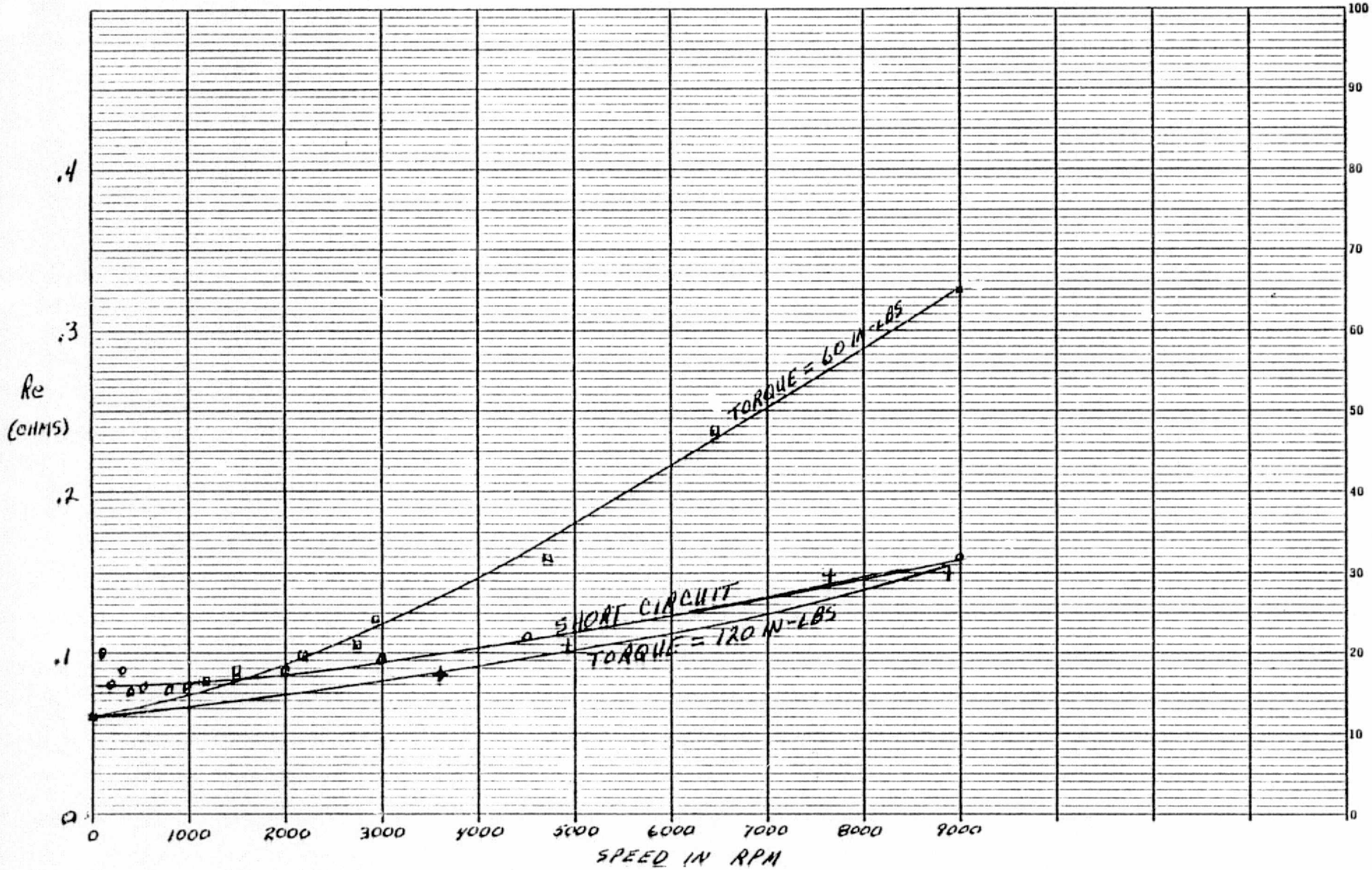


Figure 3 R_e vs Shaft RPM

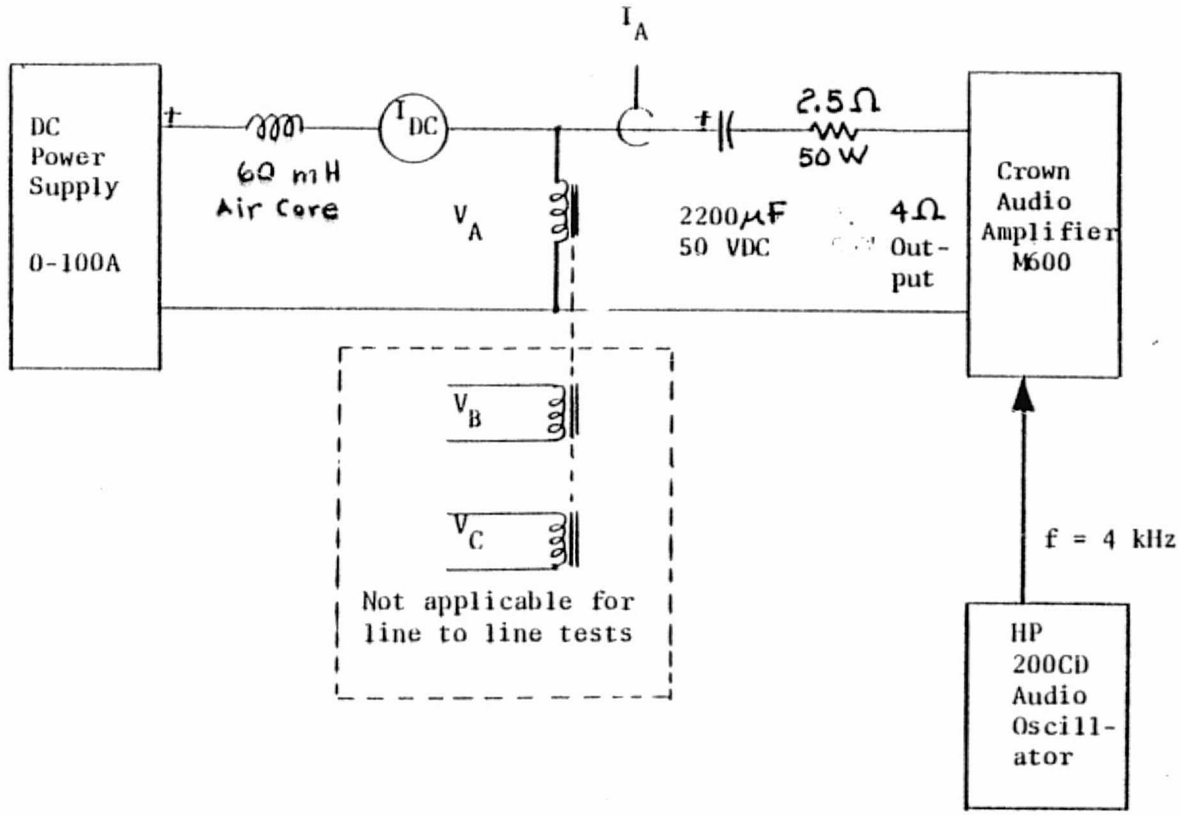


Figure 4 Incremental Inductance Test Circuit

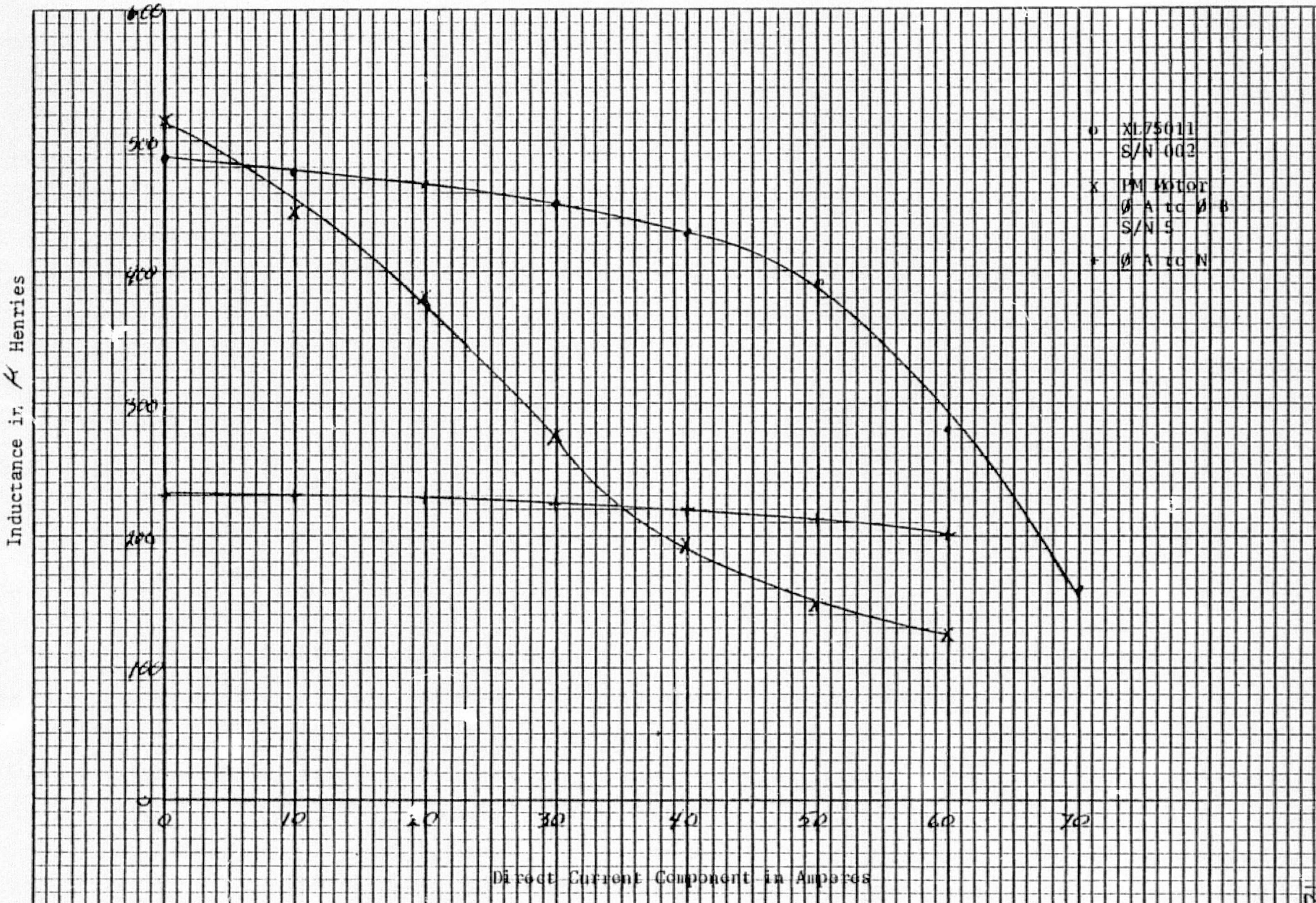
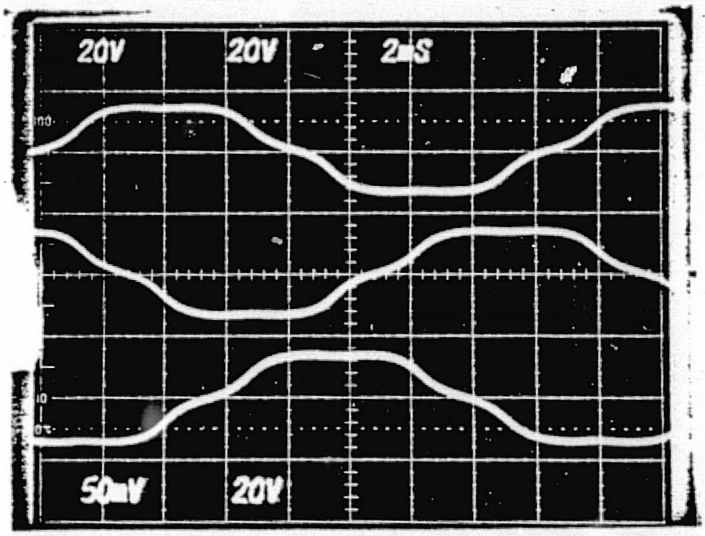


Figure 5 Incremental Inductance, Motor and Inductor

N = 900 RPM
F = 60 Hz

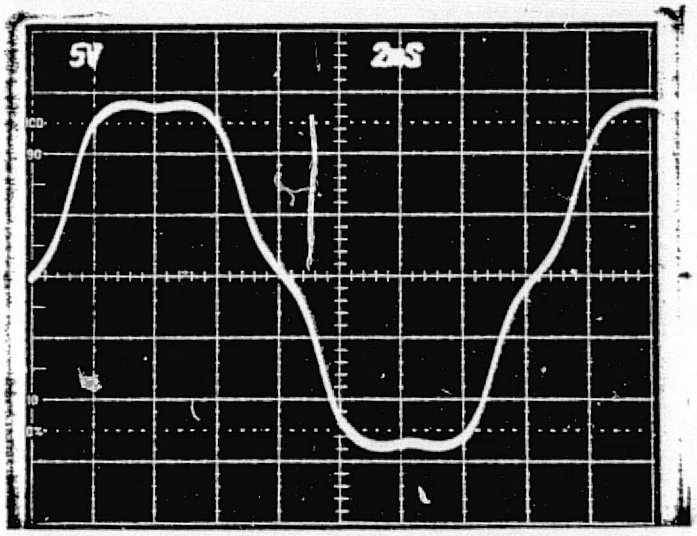


V_{C-N}

V_{B-N}

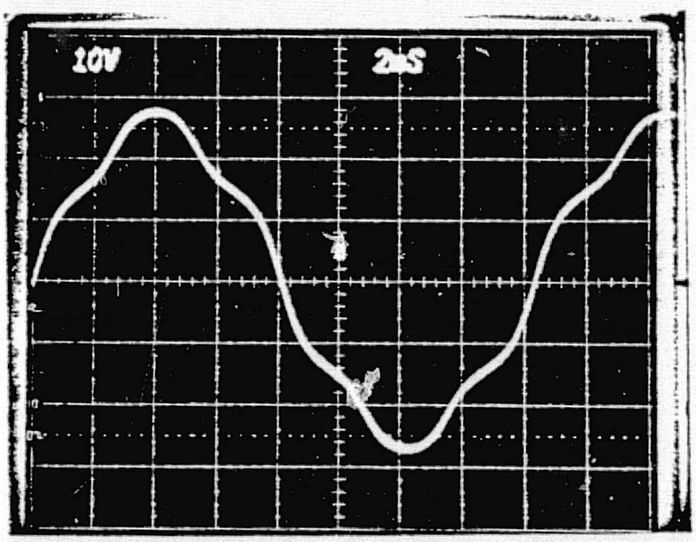
V_{A-N}

Fig. 6



V_{A-N}

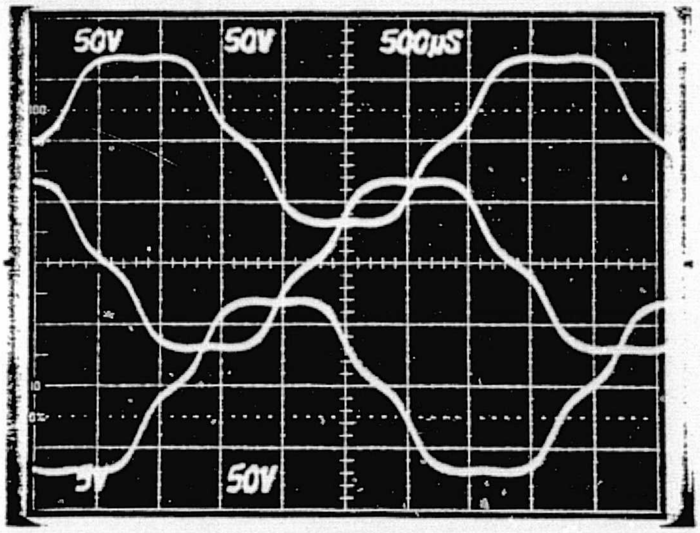
Fig. 7



V_{A-B}

Fig. 8

N = 4500 RPM
F = 300 Hz

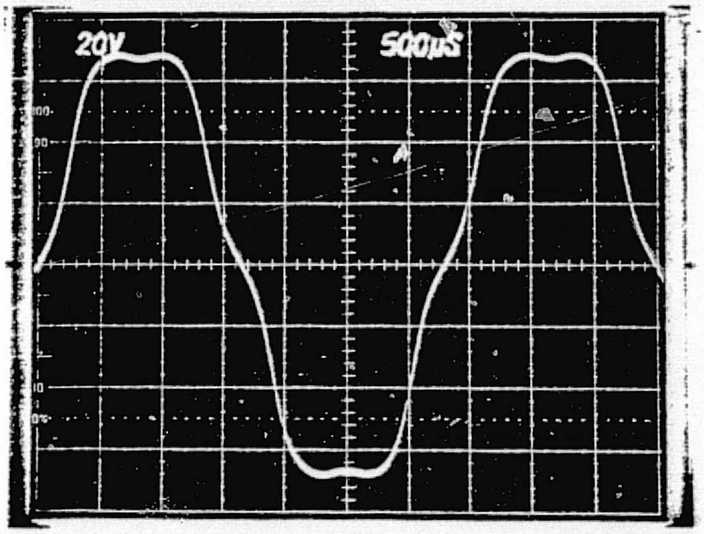


V_{C-N}

V_{B-N}

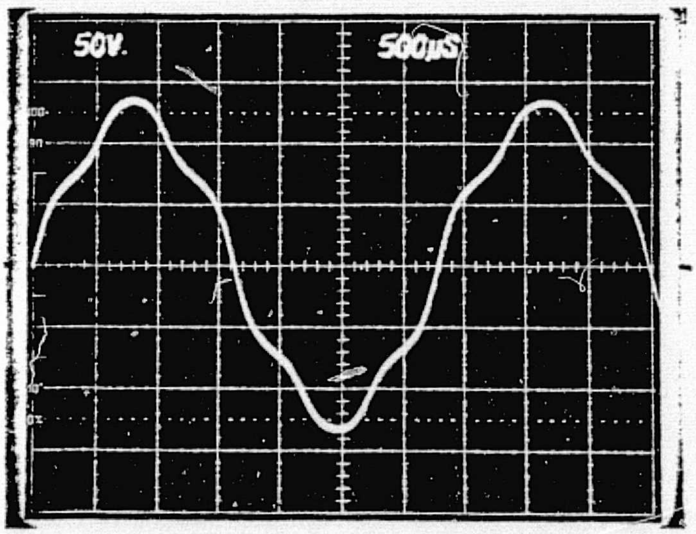
V_{A-N}

Fig. 9



V_{A-N}

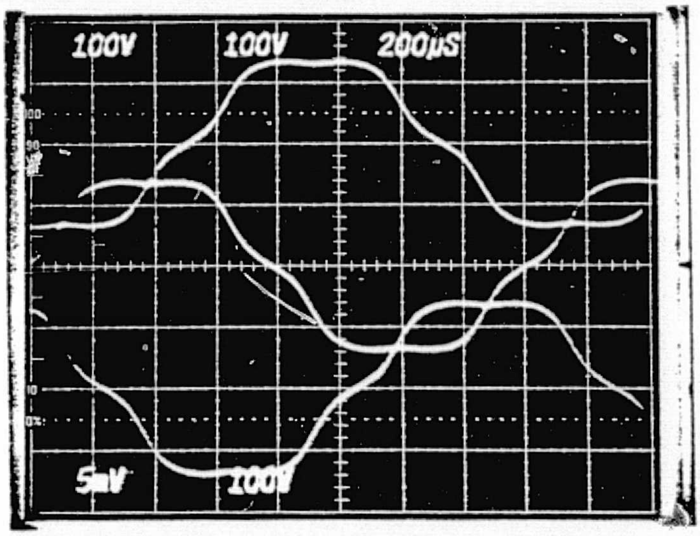
FIG. 10



V_{A-B}

Fig. 11

N = 9000 RPM
F = 600 Hz

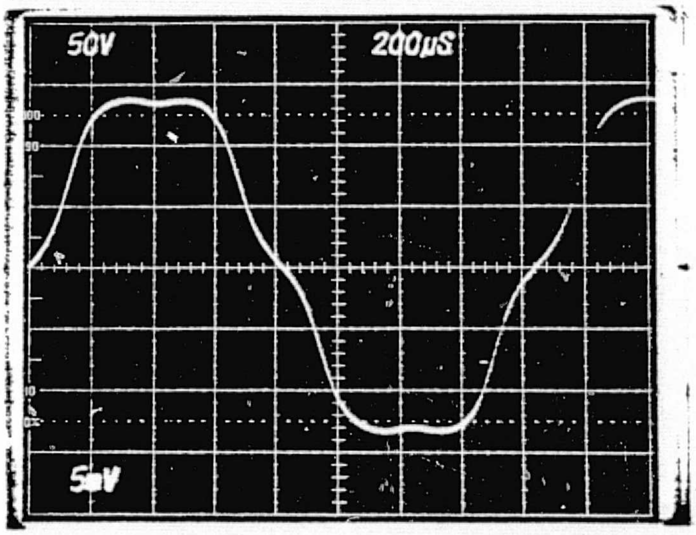


V_{C-N}

V_{B-N}

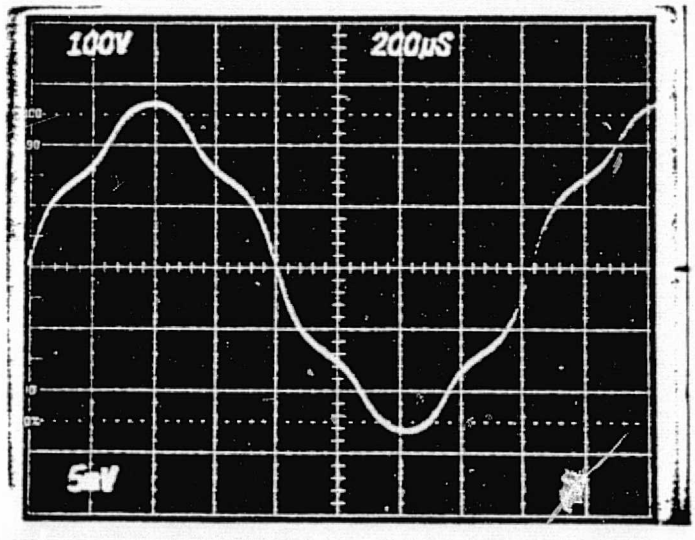
V_{A-N}

Fig. 12



V_{A-N}

Fig. 13



V_{A-B}

Fig. 14

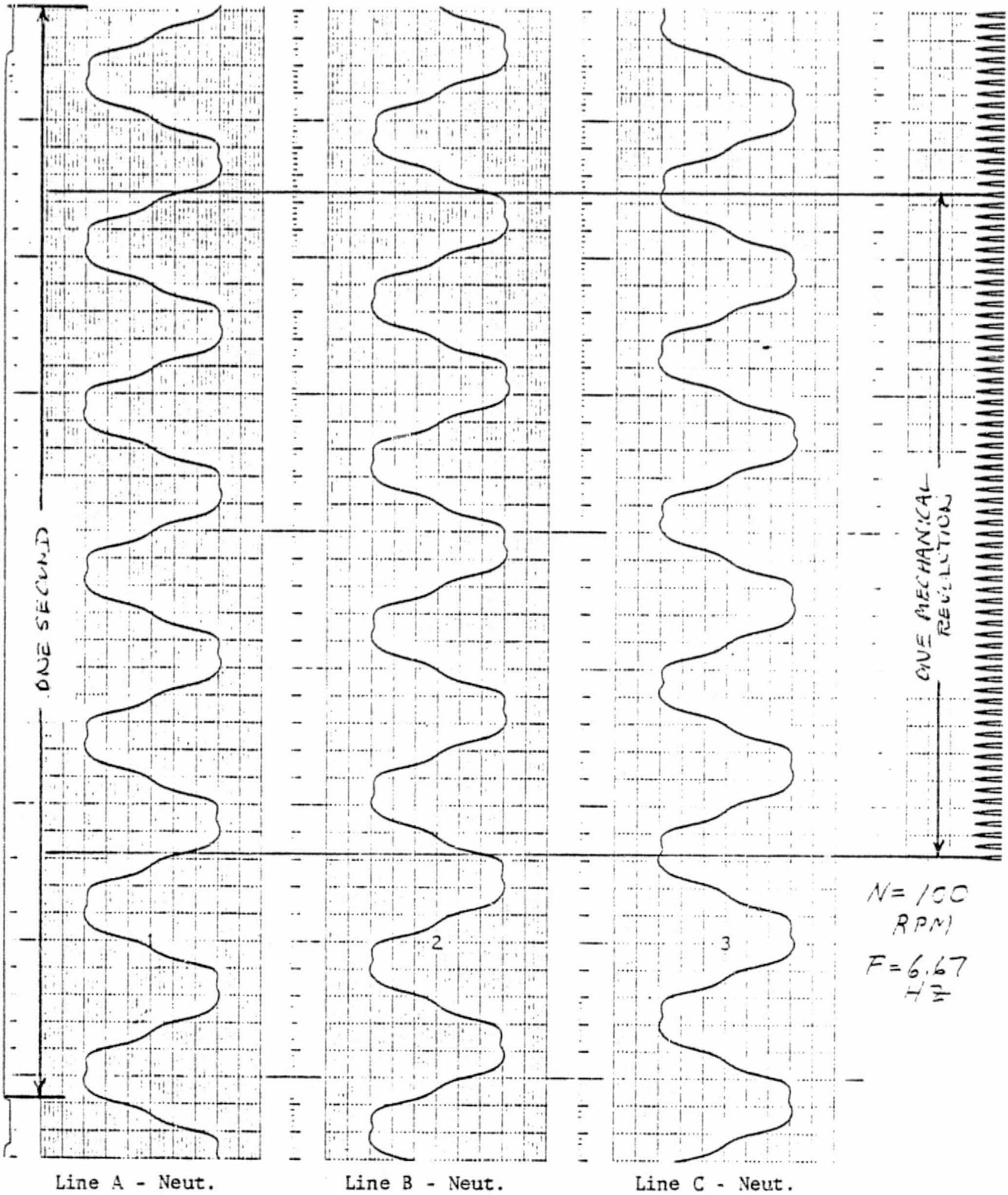


Figure 15 Line to Neutral Symmetry

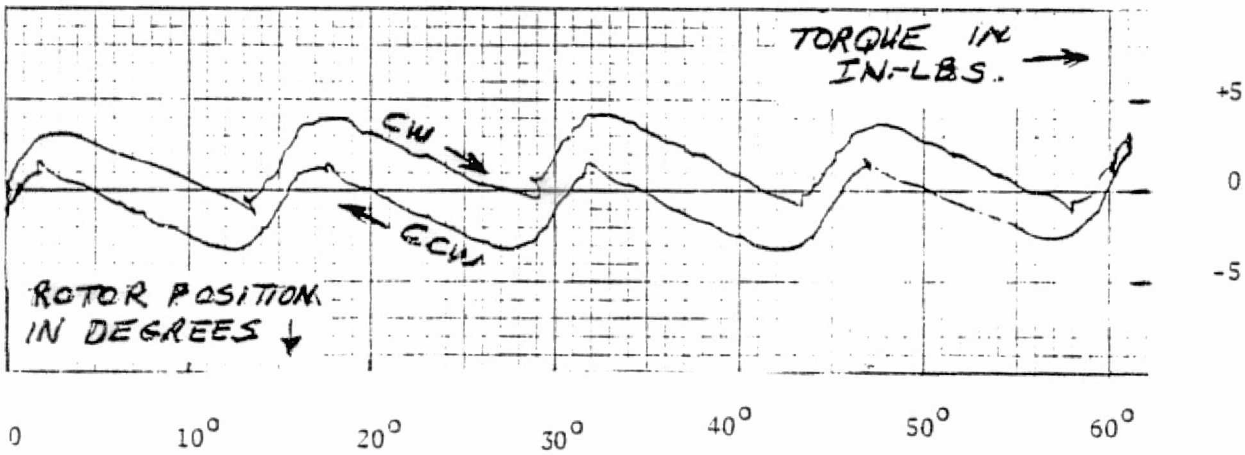


Figure 16 Cogging Torque

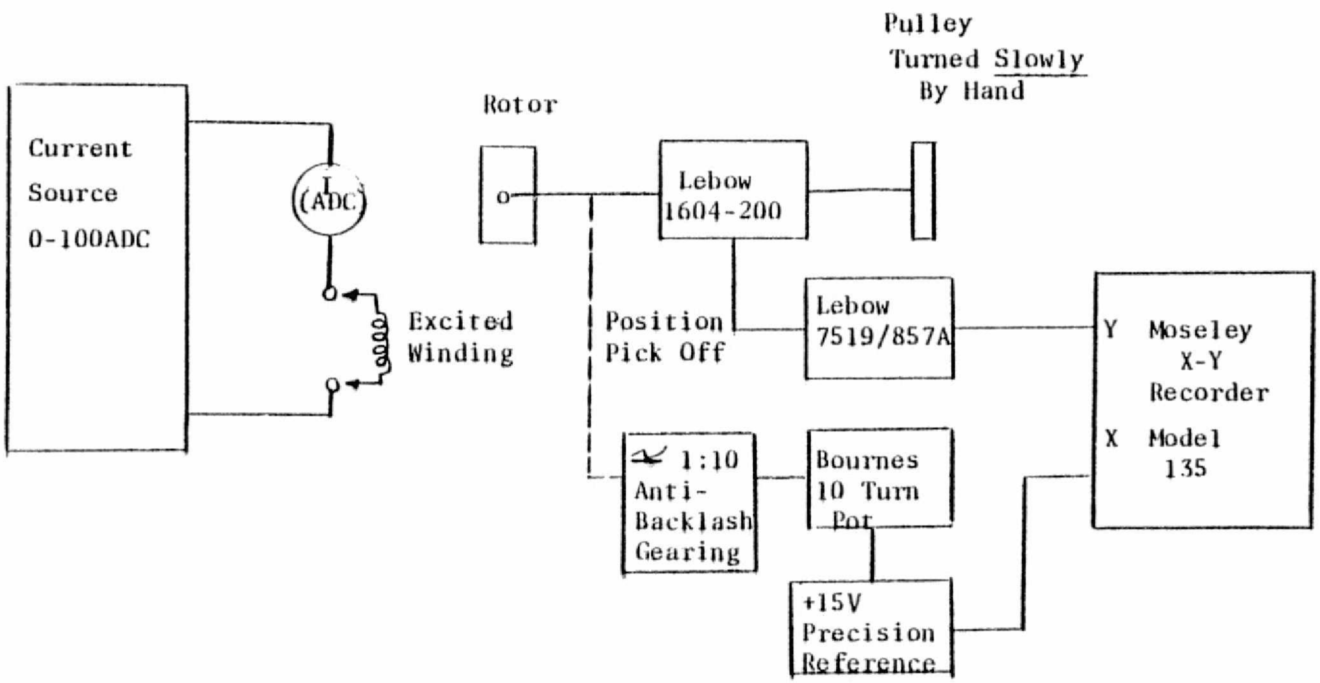
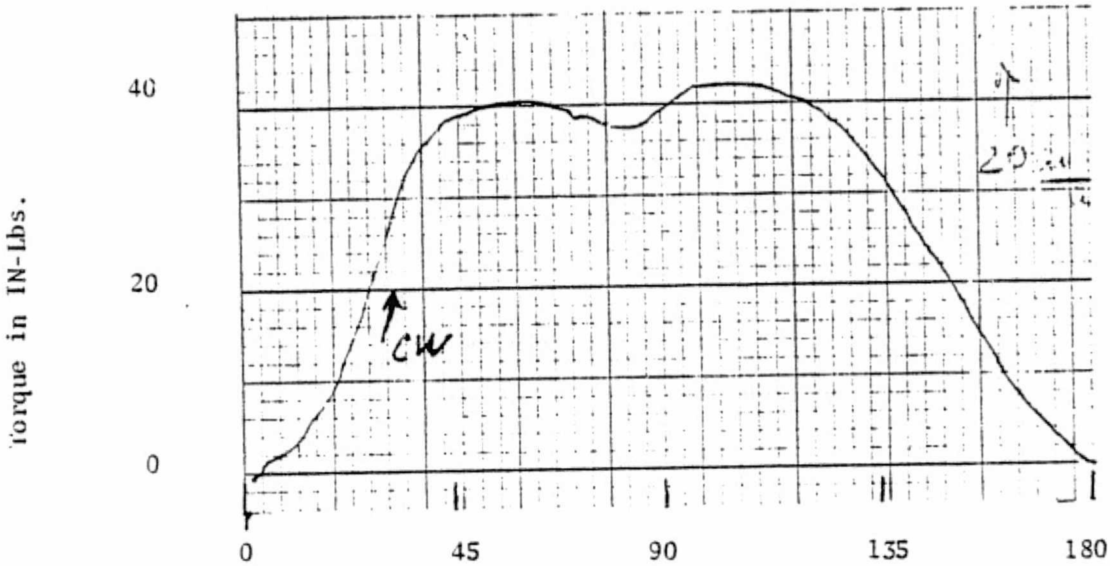


Figure 17 DC Torque Test Set Up

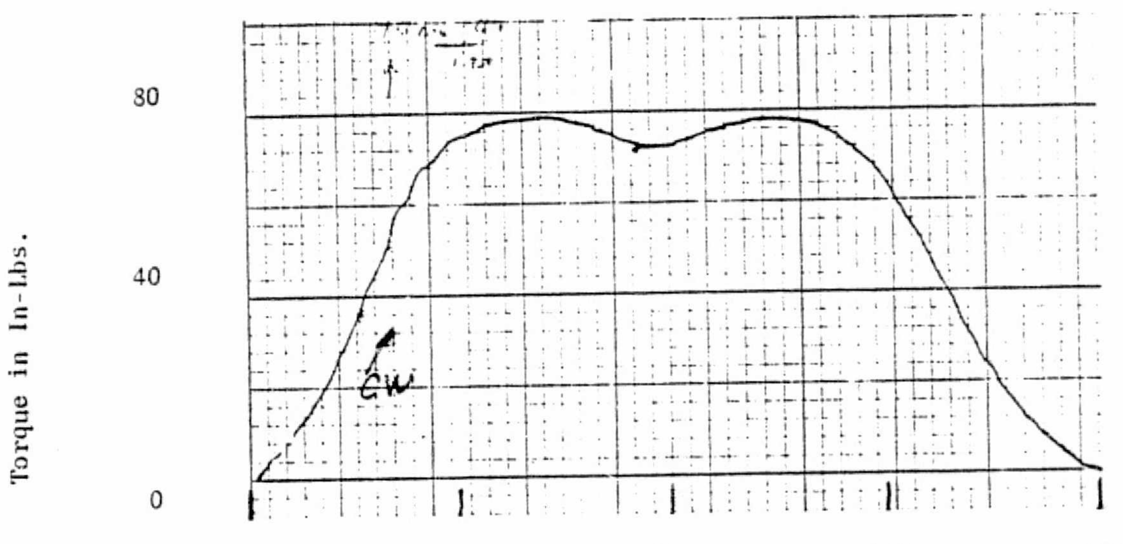


(Ref. - 7.5°
Mechanical)

Degrees (Electrical)

I Line A - Neut. = 30 ADC

Figure 18 DC Torque (30 ADC, L-N)

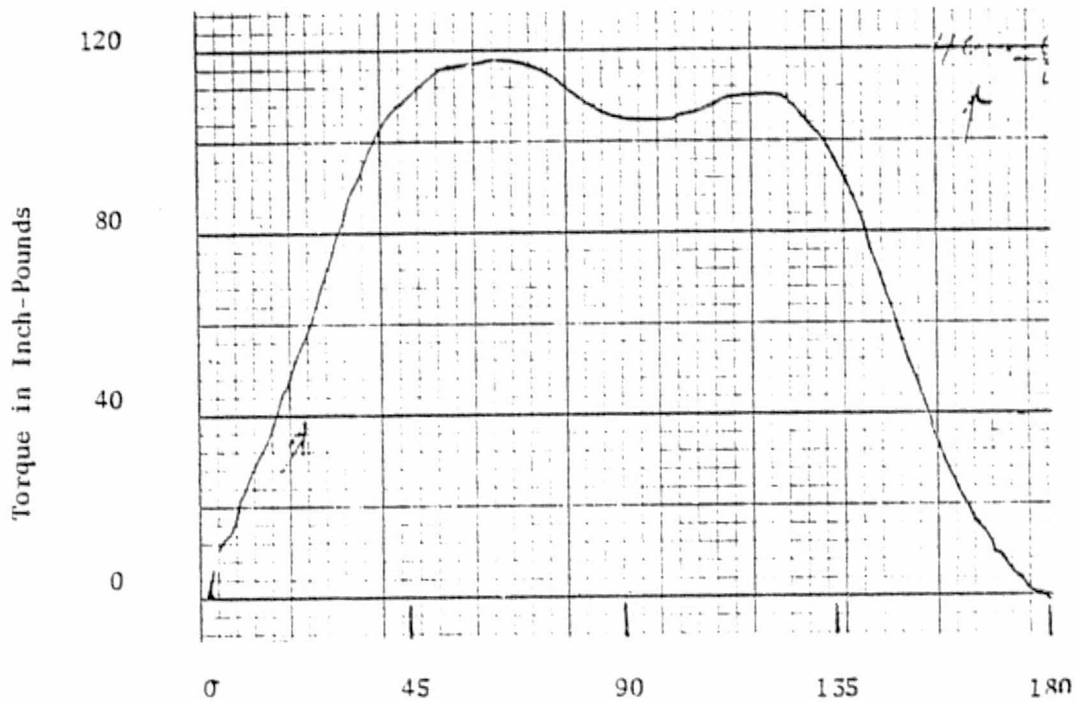


Degrees (Electrical)

(Ref. - 7.5°
Mechanical)

I Line A - Neut. = 60 ADC

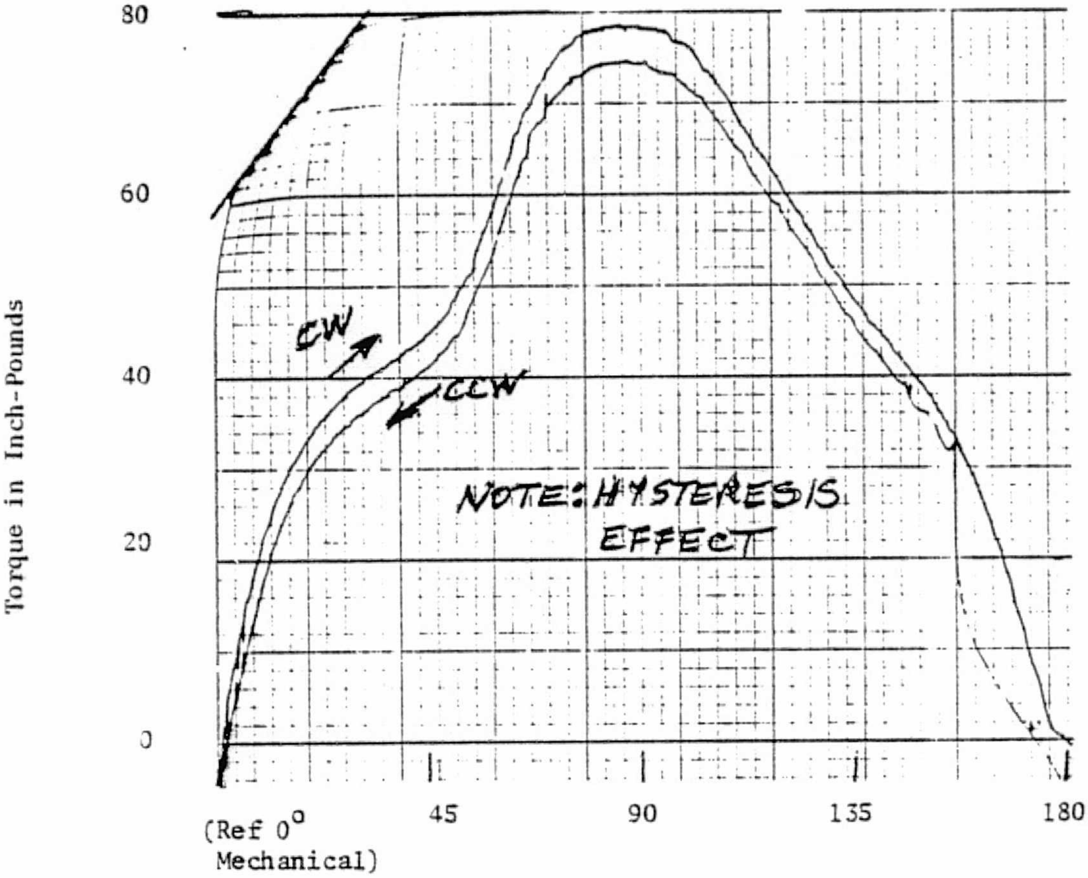
Figure 19 DC Torque (60 ADC, L-N)



(Ref. = 7.5° Mechanical)

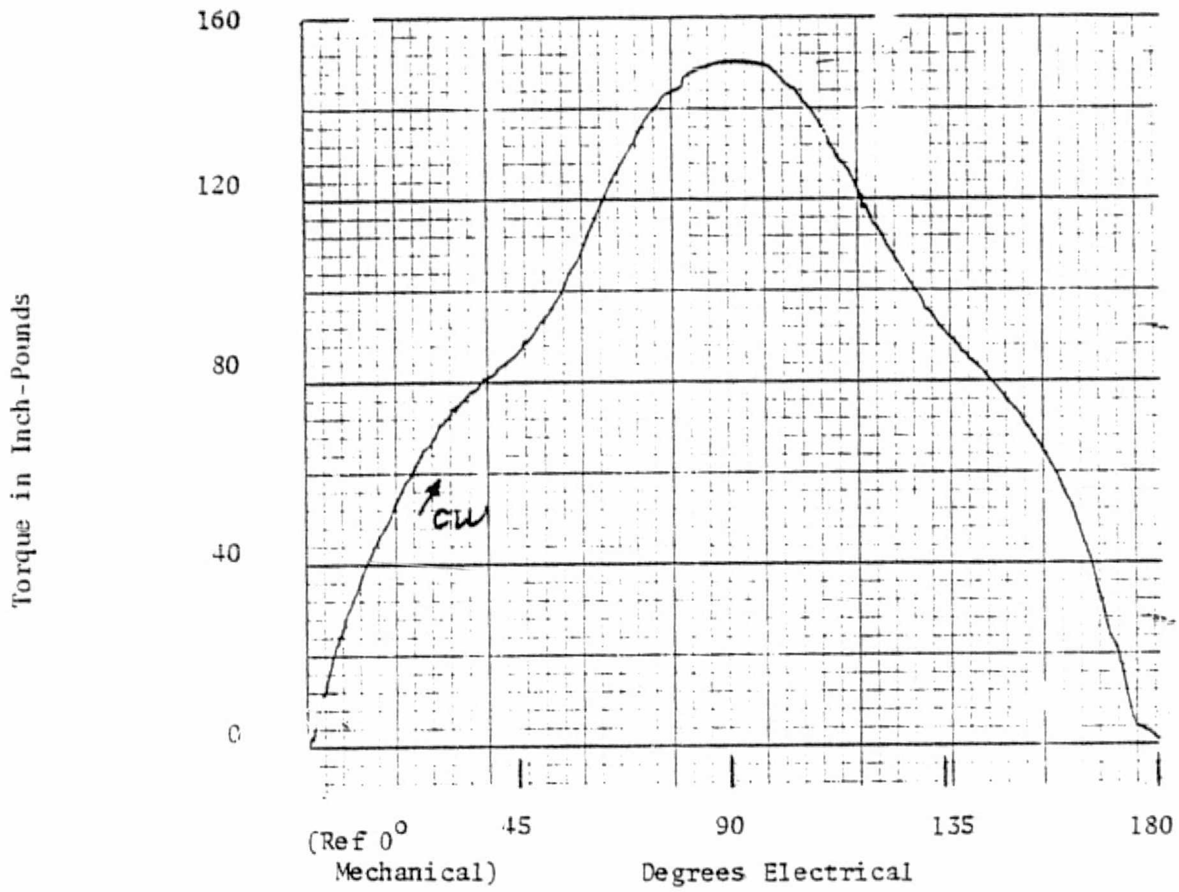
$I_{LINE\ A}$ - Neutral = 90 ADC

Figure 20 DC Torque (90 ADC, L-N)



$I_{LINE_A - LINE_B} = 30$ ADC

Figure 21 DC Torque (30 ADC, L-L)



$I_{LINE_A - LINE_B} = 60$ ADC

Figure 22 DC Torque (60 ADC I_{L-L})

K+E 1 YEAR BY MONTHS X 100 DIVISIONS 46 3170 MADE IN U.S.A. KEUFFEL & ESSER CO.

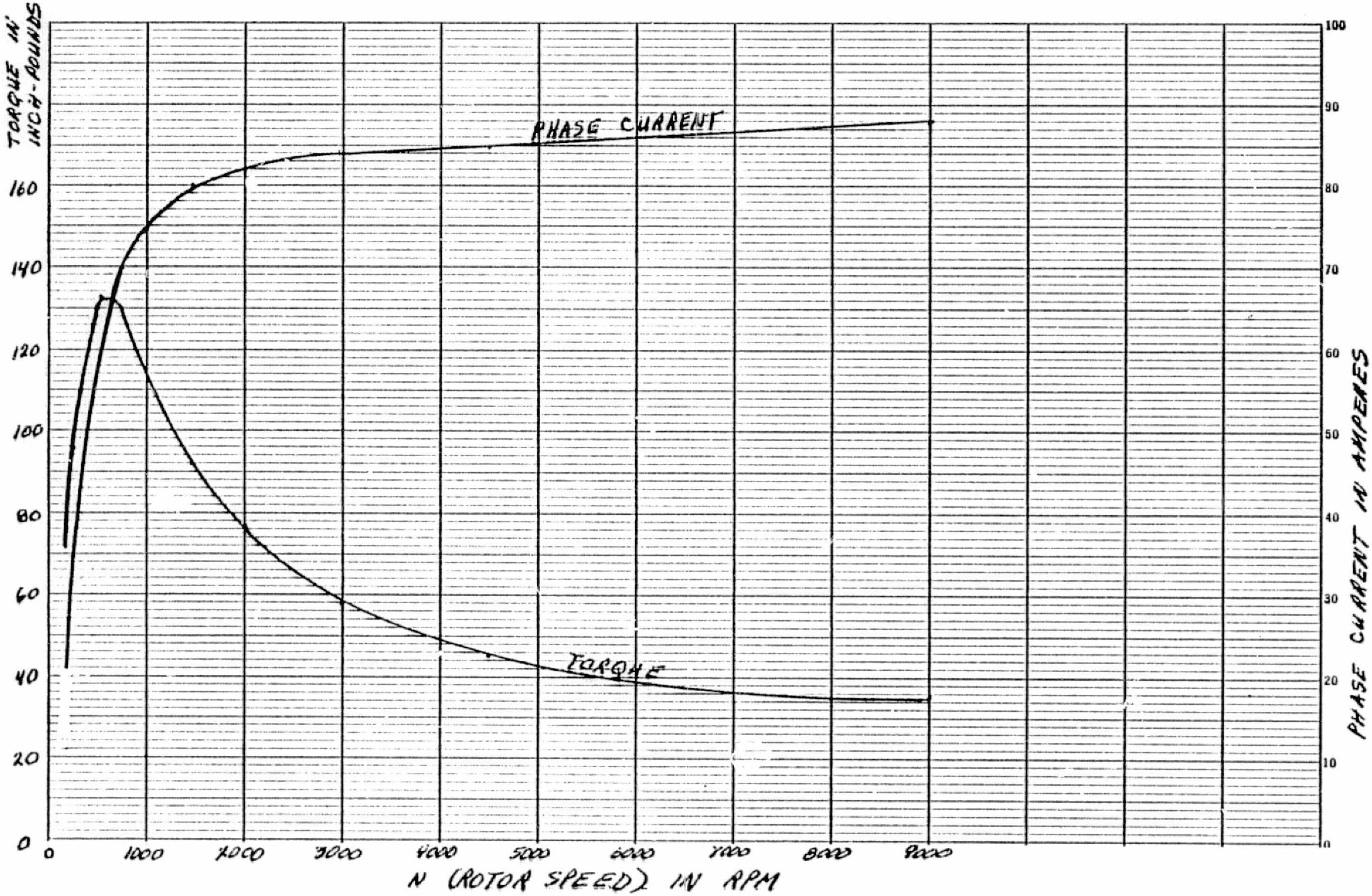


Figure 23 Short Circuit Braking

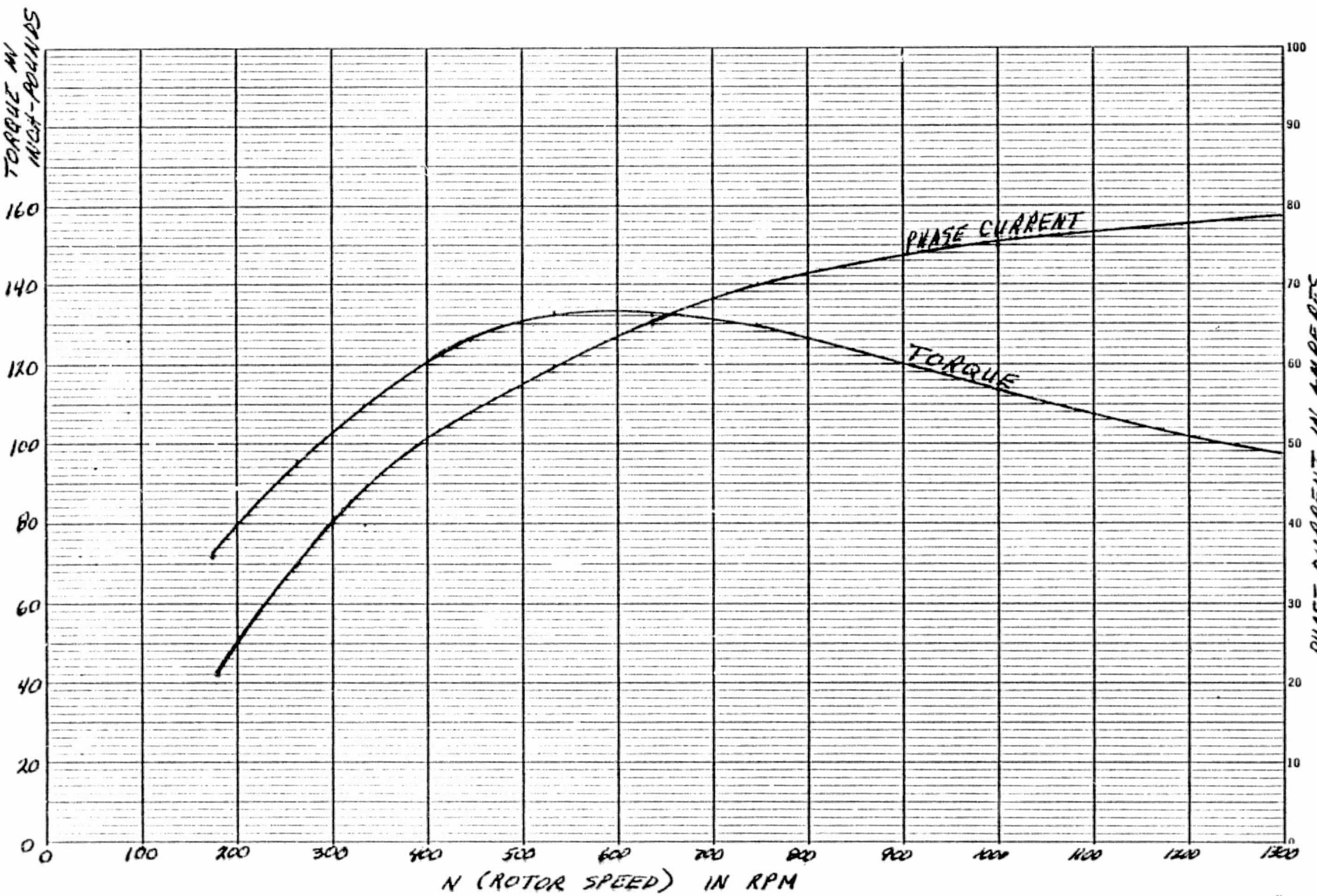


Figure 24 Short Circuit Braking

N = 262 RPM
I_A = 35 ARMS
T = 96 In.-Lbs. average

- T @ 20 In-Lbs/Div.

- I_A @ 20A/DIV

0_{IA} -

0_T -

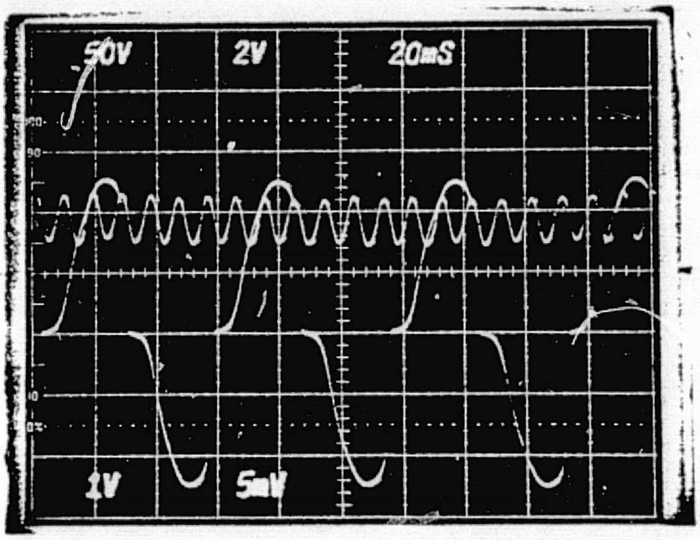
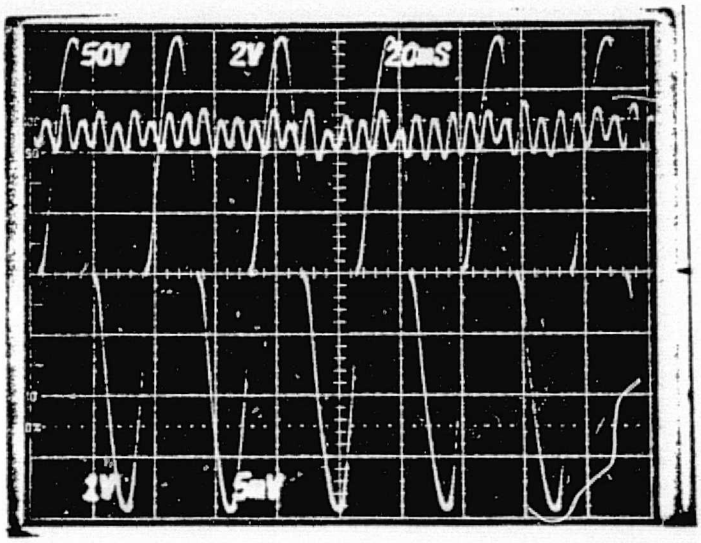


Figure 25 I_A and Torque



0_{IA}-

0_T -

- T @ 20 IN-Lbs/Div

- I_A @ 20A/Div

N = 445 RPM
I_A = 54 ARMS
T = 126 In-Lbs Average

Figure 26 I_A and Torque

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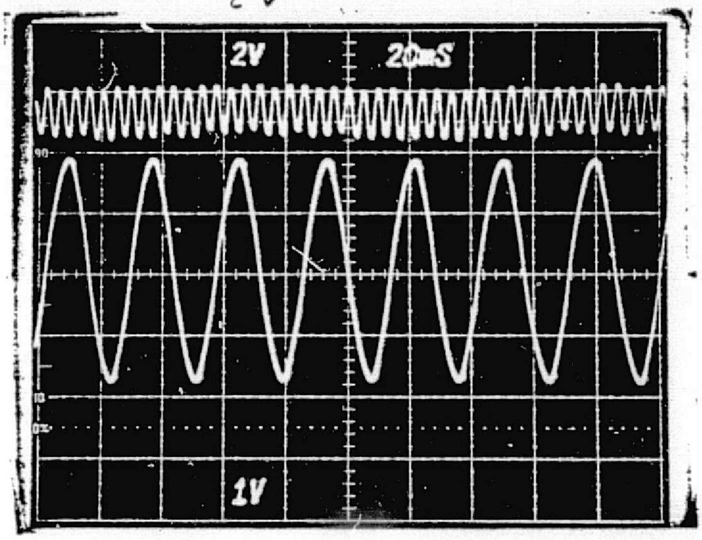
OF POOR QUALITY



T @ 20 In-Lbs/Div.

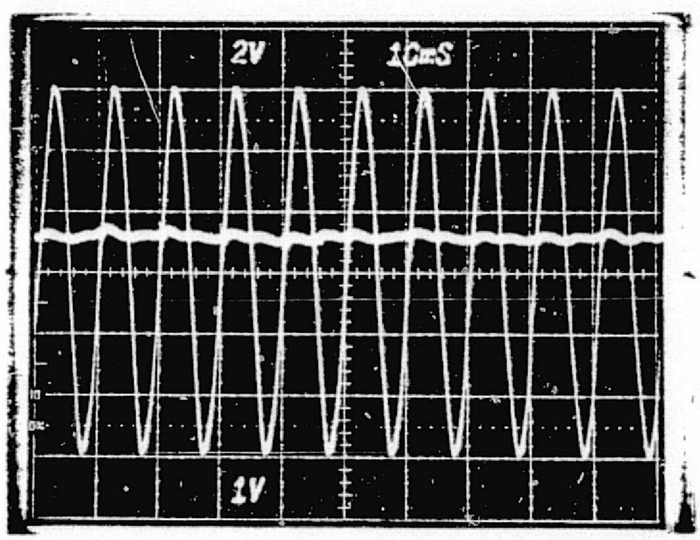
0_{IA} -

- I_A @ 50 A/Div

N - 532 RPM
I_A = 60 ARMS
T = 133 In-Lbs Average

0_T -

Figure 27 K_A and Torque



- T @ 20 In-Lbs/Div.
I_A @ 40 A/Div

0_{IA} -

N = 1500 RPM

I_A = 80 ARMS
T = 92 In-Lbs Average

0_T -

Figure 28 I_A and Torque

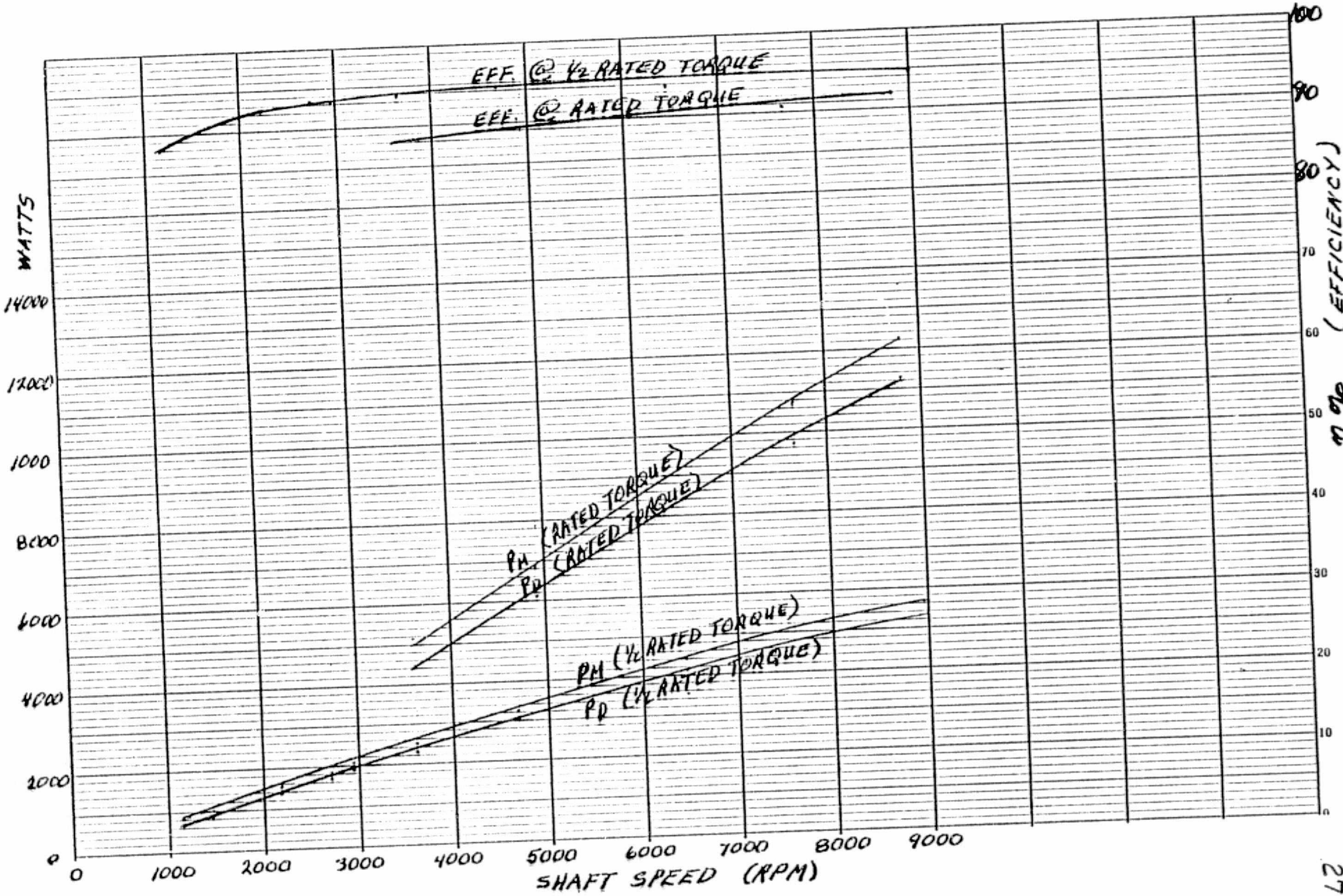


Figure 29 Loaded Alternator Performance

TABLE 1 R_e CALCULATED FROM SHORTED WINDING OPERATION

N (RPM)	Freq (HZ)	R_e (OHMS)	
0	0	0.060*	
173	11.5	0.101	
262	17.5	0.081	
333	22.2	0.090	
445	29.7	0.076	Distorted
532	35.5	0.078	Waveform
636	42.4	0.078	SINE
747	49.8	0.078	WAVE
1000	66.7	0.080	
1500	100	0.085	
2000	133.3	0.090	
3000	200	0.097	
4500	300	0.111	
9000	600	0.160	

* $R_e = R_{DC}$

TABLE 2 R_e CALCULATED FROM LOADED ALTERNATOR OPERATION

N(RPM)	T(IN-LBS)	FREQ (HZ)	R_e (OHMS)
0	0	0	0.060*
1184	60	79	0.083
1466	60	98	0.089
2197	60	146	0.098
2720	60	181	0.105
2971	60	198	0.121
3630	60	242	0.135
4687	60	312	0.159
6450	60	430	0.238
9000	60	600	0.325
0	0	0	0.060*
3600	120	240	0.087
4925	120	328	0.105
7654	120	510	0.148
8800	120	587	0.150

* $R_e = R_{DC}$

TABLE 3 R_e CALCULATED WITH EXTERNAL EXCITATION

EXC. F (HZ)	CORRES. N (RPM)	R_A (OHMS) (CORRES. R_e)	EXC. I_A (AMPS RMS)
DC	0	0.060	LOW
60	900	0.066	3.02
60	900	0.067	5.92
60	900	0.066	9.10
60	900	0.067	30.0
60	900	0.068	45.0
60	900	0.071	60.0
60	900	0.073	75.0
60	900	0.069	90.0
DC	0	0.060	LOW
400	6000	0.126(0.113)*	3.00
400	6000	0.130	6.00
400	6000	0.132	9.00
400	6000	0.136(0.109)*	30.0
400	6000	0.136	45.0
400	6000	0.139(0.098)*	60.0

* (XXX) Denotes R_A at $\delta_e = 90^\circ$, otherwise $\delta_e = 0^\circ$

TABLE 4 DEFINITION OF VARIABLES

Φ_r -	rotor flux
Φ_A -	phase A stator flux
δ_e -	electrical torque angle *
F -	electrical excitation frequency
I_A -	RMS value of ØA excitation current (or DC, if applicable)
V_A -	line A to neutral RMS voltage
V_B -	line B to neutral RMS voltage
V_C -	line C to neutral RMS voltage
Θ_A -	I_A, V_A phase angle in degrees
L_A -	line A to neutral (self) inductance
L_{B-A} -	ØB to ØA mutual inductance
L_{C-A} -	ØC to ØA mutual inductance
R_A -	line A to neutral effective series resistance

* 0 degrees reference is found by putting direct current in for I_A and finding a point of stable equilibrium. (Note that there are in 360^o mechanical rotation 4 points of stable and 4 points of unstable equilibrium. One of the former is chosen for $\delta_e = 0^o$.)

$L_A = V_{XA}/(2\pi F)I_A$ self inductance

$V_B = j(2\pi F)(L_{B-A} I_A)$

$I_A = V_{XA}/(2\pi F) L_A$

$V_B = j(2\pi F) L_{B-A} V_{XA}/(2\pi F) L_A$

$L_{B-A} = L_A (V_B/V_{XA})$ mutual to B

$L_{C-A} = L_A (V_C/V_{XA})$ mutual to C

The results of these calculations appear in Table 5.

C-2

Table 5. Inductances of a Stalled Motor at 60 Hz and 400 Hz Excitation

δ_e	F	I_A (Nominal)	L_A (Calc.)	L_{B-A} (Calc.)	L_{C-A} (Calc.)
0 deg.	60 Hz.	3 AMPS	287 μH	19.2 μH	18.4 μH
0		6	288	18.4	17.9
0		9	289	18.1	17.5
0		30	293	17.7	17.2
0		45	293	18.3	18
0		60	289	20.3	19.9
0		75	277.3	22.8	22.1
0		90	287	24.2	23.3
0	400 HZ.	3	279.3	18.6	18.6
0		6	282	18.6	17.9
0		9	282.6	18.1	17.2
0		30	286.7	17.8	17.2
0		45	286	18.4	17.7
0		60	284	20.6	19.2
			$\bar{x}$ = 286	$\bar{x}$ = 19.4	$\bar{x}$ = 18.7
			σ = 4.6	σ = 2.0	σ = 1.9
-15 deg.	60 HZ.	30 AMPS	305 μH	90.2 μH	23.4 μH
-30		3	318	186	113
-45		30	319	83.1	97.3
-90		3	326	79.5	61.9
-15	400 HZ.	3	271	33.6	16.2
-15		30	267.8	46.4	13.3
-15		60	253.4	70.3	16.8
-45		3	254.3	31.1	33.3
-45		30	246.9	43.1	46.4
-45		60	221.4	66.3	72.9

TABLE 6 LINE TO NEUTRAL INCREMENTAL INDUCTANCE ($\delta_e = 0$)

I_{DC} (AMPERES)	L_A (MICROHENRIES)
0	231
10	231
20	229
30	224
40	221
50	213
60	201

TABLE 7 LINE TO LINE INCREMENTAL INDUCTANCE ($\delta_e^* = 0$)

I_{DC} (AMPERES)	L_{A-B} (MICROHENRIES)
0	515
10	446
20	382
30	275
40	193
50	148
60	127

TABLE 8 LINE TO NEUTRAL INCREMENTAL INDUCTANCE WITH ROTOR REMOVED,* ALSO MUTUALS

I_{DC} (AMPERES)	L_A (μH)	L_{B-A} (μH)	L_{C+A} (μH)
0	241	18.4	19.1
20	239	18.4	19.3
40	239	19.5	20.1
60	235	20.1	20.5

* Serial No. 6

TABLE 9 LINE TO LINE INCREMENTAL INDUCTANCE WITH ROTOR REMOVED*

I_{DC} (AMPERES)	L_{A-B} or $L_{A-(-B)}$ (μH)
Current Flow A thru Neutral $_A$ thru B thru Neutral $_B$ (i.e., reversed B phasing)	
0	436
10	434
20	426
30	420
40	414
50	402
55	394
Current Flow A thru Neutral $_A$ thru Neutral $_B$ thru B	
0	509
20	499
40	495
50	491
60	491

* Serial No. 6

TABLE 10 CURRENT SOURCE INDUCTOR INCREMENTAL INDUCTANCE

I_{DC} (AMPERES)	L (μH)
0	487
10	477
20	468
30	452
40	430
50	392
60	279
70	160

TABLE II OPEN CIRCUIT TERMINAL VOLTAGES

	FREQ/RPM		
	60 HZ 900 RPM	300 HZ 4500 RPM	600 HZ 9000 RPM
V_A (TRUE RMS VOLTAGE)	10.59	52.71	105.3
V_{A-B} (TRUE RMS VOLTAGE)	18.33	91.50	182.2
V_A (AVG. RESPONDING, RMS INDICATING)	10.42	51.90	103.6
V_{A-B} (AVG RESPONDING, RMS INDICATING)	18.65	92.90	185.6
V_A (PEAK TO PEAK)	27.0	136	270
V_{A-B} (PEAK TO PEAK	53.6	265	536

TABLE 12 DC TORQUE VERSUS CURRENT

$I_{\text{Line - Neut}}$ (ADC)	$I_{\text{Line-Line}}$ (ADC)	Torque (In-Lbs)
30	-	42
60	-	79
90	-	119
0	0	4*
-	30	79
-	60	152

*Cogging Component (which is superimposed on the excited values)

TABLE 13 SHORT CIRCUIT BRAKING DATA

N (RPM)	T (IN.-LBS)	I_{PHASE} (ARMS)	P_{INPUT} (WATTS)
173	72	22	147
262	96	35	298
333	110	40	433
445	126	54	663
532	133	60	837
636	132	65	993
747	130	70	1149
1000	114	75	1349
1500	92	80	1633
2000	77	82	1822
3000	58	84	2059
4500	45	85	2396
9000	35	88	3727

TABLE 14 SYMMETRICAL 3 PHASE LOAD TEST DATA

N(RPM)	T(IN.-LBS.)	P_M(WATTS)*	P_D LOAD(WATTS)	P_D MOTOR(WATTS)	η (%)
1184	58.00	813.7	717.0	96.7	88.1
1466	58.09	1007.4	903.8	103.6	89.7
2197	58.09	1509.8	1394.8	115.0	92.4
2720	58.09	1869.2	1745.9	123.3	93.4
2971	58.09	2041.7	1901.0	140.7	93.1
3630	58.09	2494.6	2337.6	157.0	93.7
4687	58.09	3220.9	3037.6	183.3	94.3
6450	58.09	4432.5	4160.0	272.5	93.9
9000	53.31	5675.9	5369.9	306.0	94.6
3600	117.8	5016.9	4409.4	607.5	87.9
4925	117.8	6863.4	6129.2	734.2	89.3
7654	117.8	10666.4	9678.7	987.7	90.7
8800	117.8	12263.5	11283.4	980.1	92.0
2250	1.37	36.5	0	36.5	-
4500	1.51	80.4	0	80.4	-
6750	1.63	130	0	130	-
9000	1.79	191	0	191	-

* SHAFT INPUT POWER TO MOTOR = KNT

APPENDIX F

EFFICIENCY TESTS

This appendix presents Delco document EE-22T-EMA-020, which covers efficiency tests conducted on the motor, the drive control electronics and the overall system.

Delco Electronics — General Motors Corporation, Santa Barbara Operations, 6767 Hollister Avenue, Goleta, California 93017	EE- 22T-EMA-020	REV
	ENGINEERING EXHIBIT	
TITLE: Electromechanical Actuator Efficiency Tests	BY: J. Anselmi	SHEET 1 OF 7
	APPROVED: A. Barrett *A. Barrett*	DATE: 11/30/77

Dynamometer tests were conducted in both the motoring and regenerative braking modes to determine the efficiencies of the motor and electronic subsystems. Typical data from these measurements are summarized in Tables 1 through 4 .

The input power from the battery was measured using a digital voltmeter to monitor the battery voltage ($V_{DC\ IN}$), and a precision current shunt and digital voltmeter to measure the battery current flowing into the system ($I_{DC\ IN}$). Since the battery voltage and current are virtually constant, the input power ($P_{DC\ IN}$) is the product of $V_{DC\ IN}$ and $I_{DC\ IN}$.

Power flow into the motor was measured using the two-Wattmeter method. The Wattmeter readings were taken with a precision electronic Wattmeter having broad frequency response (YEW 2885-16 w/2805). The two Wattmeter readings are designated $W_{1\ AC}$ and $W_{2\ AC}$ respectively, and the power into the motor ($P_{To\ Mtr}$) is the sum of the two Wattmeter readings.

The mechanical power (P_{shaft}) was determined from speed-torque measurements, using

$$P_{shaft} = 0.011832\ TN \text{ Watts}$$

where T is the shaft torque (measured in in-lbs), and N is the shaft speed (in rpm).

The motor's shaft speed was read out on an electronic counter using a toothed wheel and magnetic pick-up. The shaft torque was read out from a Lebow torque transducer.

During the course of the measurements, the battery voltage changed somewhat (especially at high power levels). Therefore, in most instances, two sets of readings were taken for a given operating condition (for example, lines 1 and 2 of Table 1). Averages of the two typical sets of data were used to make the efficiency calculations presented in the last three columns of the tables.

Line	$V_{DC\ IN}$ Volts	$I_{DC\ IN}$ Amps	$P_{DC\ IN}$ Watts	W_1 AC Watts	W_2 AC Watts	$P_{To\ Mtr}$ Watts	SPEED rpm	TORQUE in-lbs	P_{Shaft} Watts	EFFICIENCIES Motor	Electronic	Overall
1	254.0	11.40	2895.6	1219	1430	2649	3050	65.6	2367			
2	253.3	11.36	2877.5	1210	1432	2642	3035	65.4	2348			
Avg 1-2			2886.6			2645.5			2357.5	89.1%	91.6%	81.6%
3	247.4	24.54	6071.2	2832	2975	5807	5940	76.1	5347.6			
4	246.0	24.56	6041.8	2818	2967	5785	5876	76.1	5289.9			
Avg 3-4			6056.5			5796			5318.8	91.8	95.7	87.8
5	244.7	28.00	6851.6	3228	3482	6710	7890	67.0	6253.7			
6	243.1	28.12	6836.0	3200	3480	6680	7838	67.0	6212.5			
Avg 5-6			6843.8			6695			6233.1	93.1	97.8	91.1
7	269.0	1.788	481.0	0	0	0	0	86.0	0.0			

TABLE 1. EFFICIENCY DATA, MOTORING MODE, AT APPROXIMATELY FULL ATTAINABLE TORQUE

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Line	$V_{DC\ IN}$ Volts	$I_{DC\ IN}$ Amps	$P_{DC\ IN}$ Watts	W_1 AC Watts	W_2 AC Watts	$P_{To\ Mtr}$ Watts	SPEED rpm	TORQUE in-lbs	P_{Shaft} Watts	EFFICIENCIES Motor	Electronic	Overall
9	258.5	6.86	1773.3	1099	495	1594	3041	39.8	1431.8			
10	257.1	6.77	1740.6	1089	480	1569	3003	39.0	1385.5			
Avg 9-10			1757.0			1581.5			1408.7	89.1%	90.0%	80.2%
11	251.1	12.22	3068.3	2022	947	2969	6061	37.7	2703.2			
12	250.6	12.30	3082.4	2007	940	2947	6103	37.0	2671.3			
Avg 11-12			3075.4			2958			2687.2	90.8	96.2	87.4
13	256.5	14.95	3834.7	2391	1348	3739	8700	34.0	3499.3			
14	255.1	14.85	3788.2	2425	1350	3775	8664	33.5	3433.6			
Avg 13-14			3811.5			3757			3466.5	92.3	98.6	90.9
15	268.5	.580	155.7	-	-	-	0	43.0	-			

TABLE 2. EFFICIENCY DATA, MOTORING MODE, AT APPROXIMATELY HALF ATTAINABLE TORQUE

Line	$V_{DC\ IN}$ Volts	$I_{DC\ IN}$ Amps	$P_{DC\ IN}$ Watts	W_1 AC Watts	W_2 AC Watts	$P_{To\ Mtr}$ Watts	SPEED rpm	TORQUE in-lbs	P_{Shaft} Watts	EFFICIENCIES Motor	Electronic	Overall
17	317.2	-21.0	-6661.2	-3858	-3294	-7152	8060	-81	-7723.3			
18	319.3	-20.9	-6673.3	-3851	-3295	-7146	8064	-81	-7709.9			
Avg 17-18			-6667.3			-7149			-7716.6	92.6%	93.3%	86.4%
19	311.8	-15.0	-4677.0	-2779	-2332	-5111.0	5985	-79.5	-5628.8			
20	312.4	-15.0	-4686.0	-2771	-2350	-5121.0	5980	-79.0	-5588.7			
Avg 19-20			-4681.5			-5116.0			-5608.8	91.2	91.5	83.5
21	296.1	-7.25	-2146.7	-1319	-1143	-2462.0	3010	-77.5	-2759.6			
22	296.2	-7.24	-2144.5	-1315	-1144	-2459.0	3000	-77.6	-2754.0			
Avg 21-22			-2145.6			-2460.5			-2756.8	89.3	87.2	77.8

TABLE 3 . EFFICIENCY DATA, REGENERATIVE MODE, AT APPROXIMATELY FULL ATTAINABLE TORQUE

Line	$V_{DC\ IN}$ Volts	$I_{DC\ IN}$ Amps	$P_{DC\ IN}$ Watts	W_1 AC Watts	W_2 AC Watts	$P_{To\ Mtr}$ Watts	SPEED rpm	TORQUE in-lbs	P_{Shaft} Watts	EFFICIENCIES Motor	Electronic	Overall
23	277.8	-3.39	-941.7	-551	-504	-1055	3016	-34	-1213.1			
24	280.9	-3.357	-943.0	-551	-503	-1054	3015	-34	-1212.7			
Avg 23-24			-942.4			-1054.5			-1212.9	86.9%	89.4%	77.7%
25	287.9	-7.423	-2137.1	-1205	-1073	-2278	6001	-36.5	-2591.2			
26	289.1	-7.405	-2140.8	-1209	-1072	-2281	6026	-37.0	-2637.6			
Avg 25-26			-2138.9			-2279.5			-2614.4	87.2	93.8	81.8
27	295.1	-9.875	-2914.1	-1605	-1440	-3045	8081	-36	-3441.5			
28	296.3	-9.875	-2926.0	-1614	-1441	-3055	8131	-36	-3462.8			
Avg 27-28			-2920.0			-3050			-3452.2	88.2	95.7	84.6

TABLE 4. EFFICIENCY DATA, REGENERATIVE MODE, AT APPROXIMATELY HALF ATTAINABLE TORQUE

Figure 1 is a plot of the efficiencies determined for the higher torque conditions. In general, the efficiencies increase with increasing power output, and the system is somewhat more efficient in the motoring mode than it is in the regenerative braking mode.

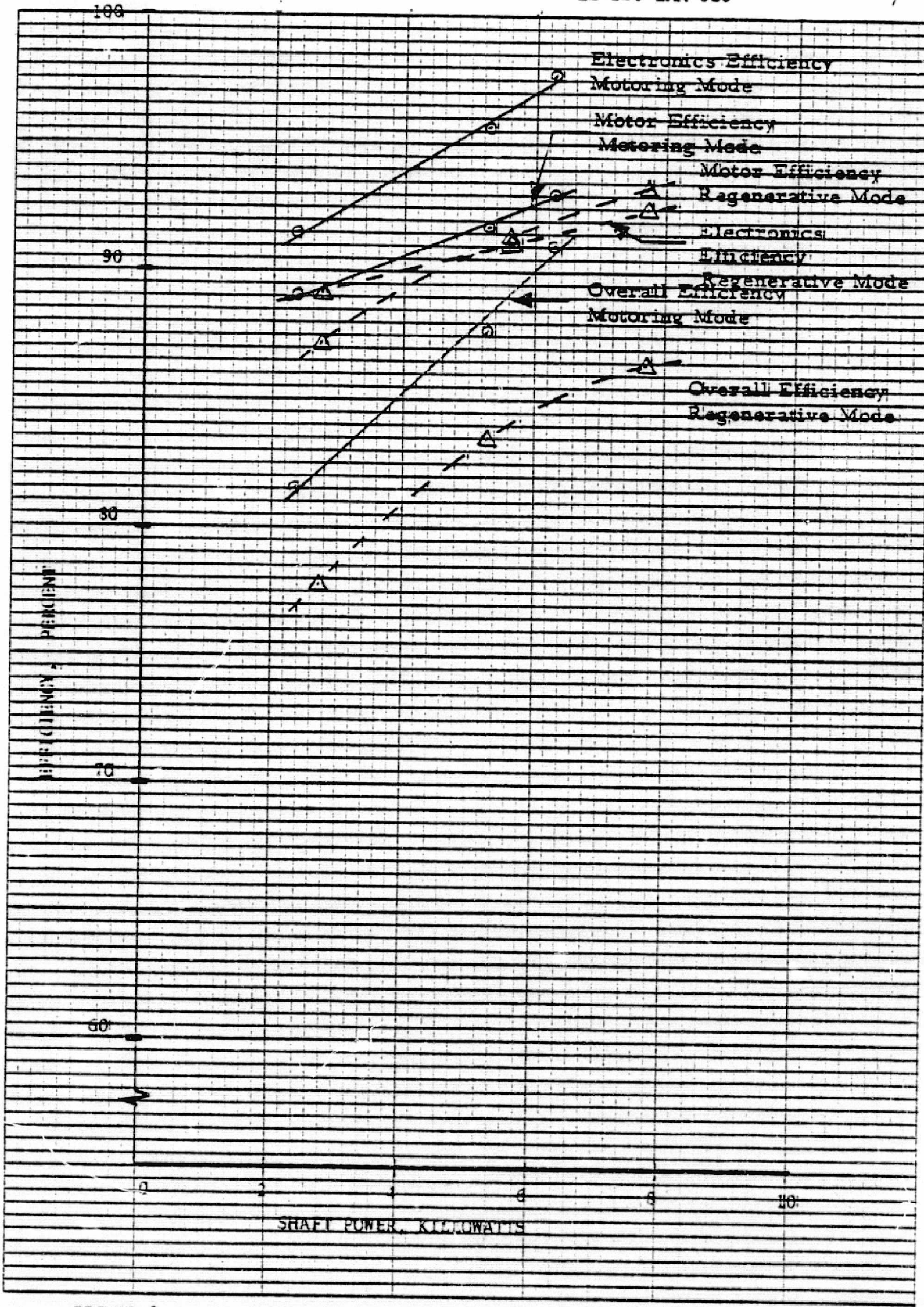

FIGURE 1 . EFFICIENCIES AS A FUNCTION OF LOAD CONDITION

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APPENDIX G

LOW-LEVEL ELECTRONICS TESTS

This appendix presents Delco document EE-22-T-EMA-012, which covers the low-level electronics tests conducted on the EMA.

Delco Electronics

GENERAL MOTORS CORPORATION
SANTA BARBARA OPERATIONS
6767 HOLLISTER AVENUE
GOLETA, CALIFORNIA 93017

EE- 22-T-EMA-012

ENGINEERING EXHIBIT
(NO CHANGE CONTROL)

TITLE: Electromechanical Actuator Tests

BY: J. Anselmi *J. Anselmi*

APPROVED: *R.H. Bassett* DATE: 7/20/77

Lab tests of the low power electronics for all four channels have just been completed. Data included in this report are from Channel D but are also representative of all four channels. The tests exercised the following circuitry:

- o RPS and associated logic.
- o Analog circuitry including tachometer and position pickoff
- o Plugging logic
- o CVR with simulated load and also common mode rejection.

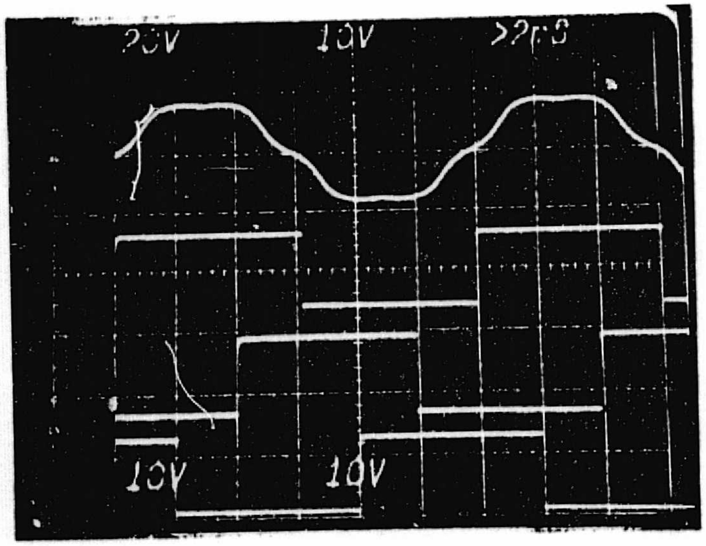
All the scope pictures and strip charts are labeled as to variable and wiring pin connector and should be self explanatory.

V_{AN}

A
E11-1

B
E2-1

C
E3-1



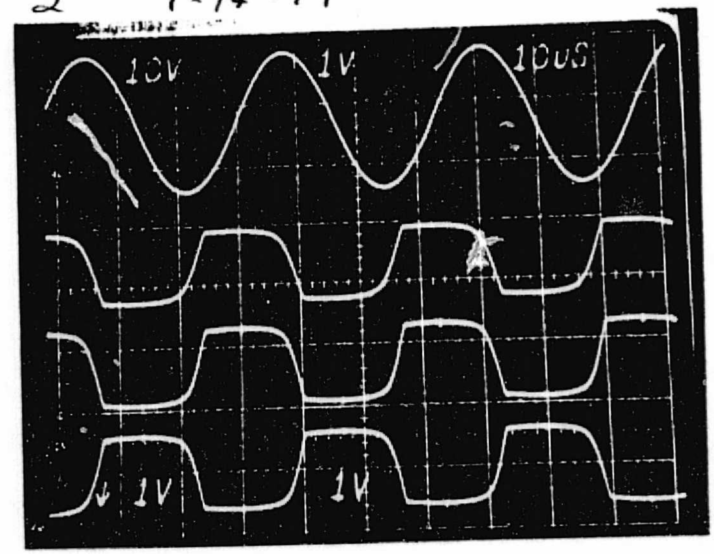
2 7-14-77

OSC
E-J2-1

RPSA
E-J2-4

RPSB
E-J2-6

RPSC
E-J2-8



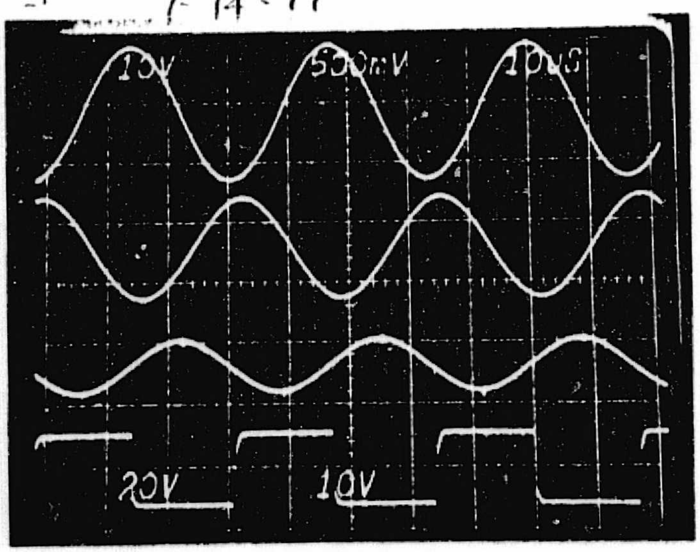
3 7-14-77

OSC.
E-J2-1

RPSIN
E-J2-2

Ref Comp.
IN
E5-2

Ref Comp.
E1-2



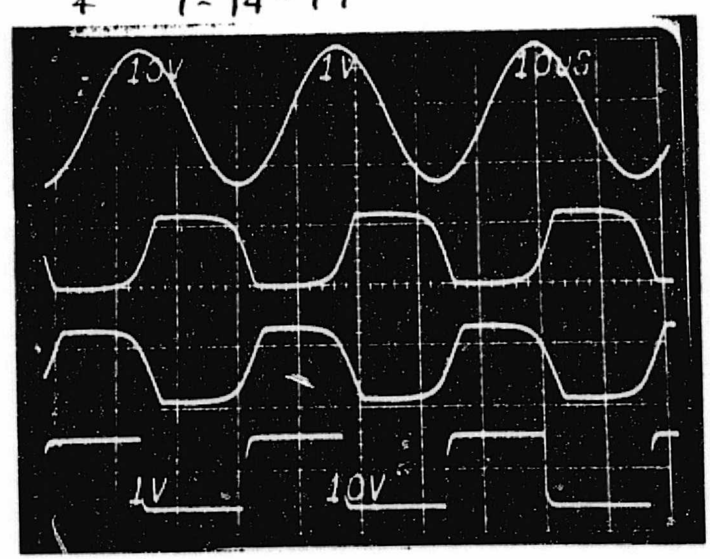
4 7-14-77

OSC
E-J2-1

RPSA
E-J2-4

Amp A
E4-1

Ref Comp.
E2-2



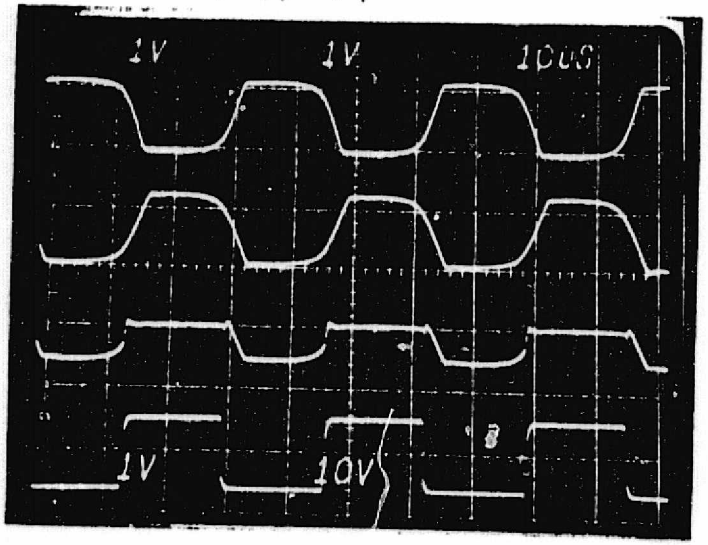
5 7-14-77

RPSA
E-J2-4

E4-1

E16-1

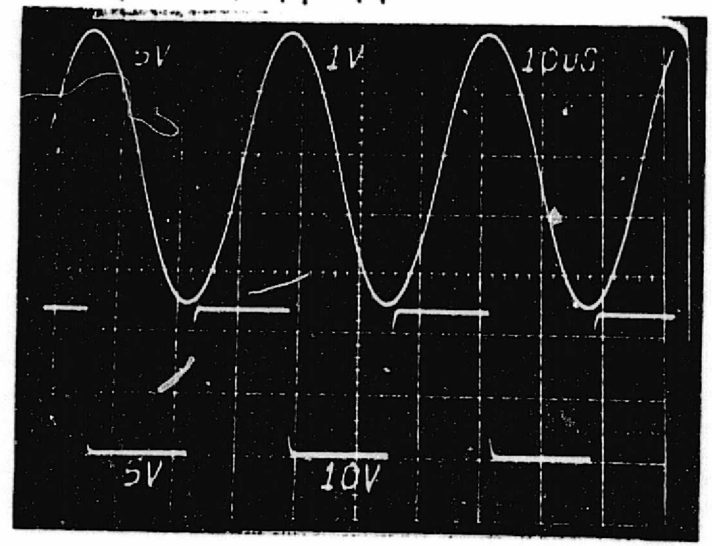
Ref Comp
E2-2



6 7-14-77

Osc out
E-J2-1

Ref Comp.
E11-15



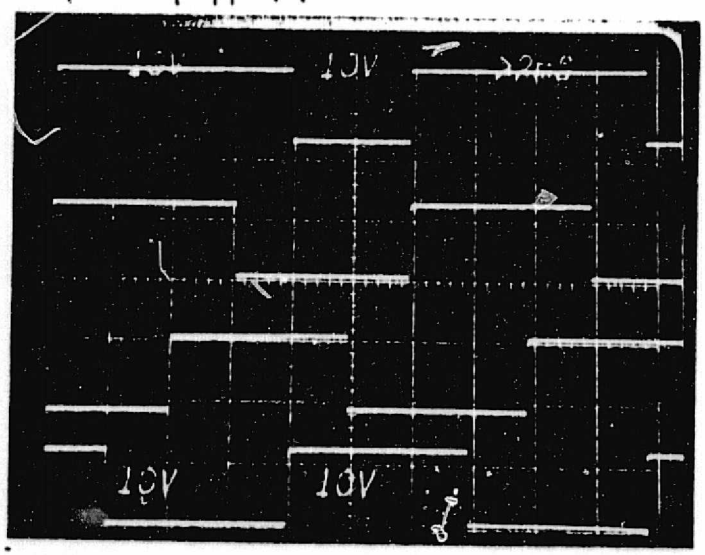
7 7-14-77

F=0
$\overline{QAPON}$
C3-4

A
E17-15

B
E2-1

C
E3-1



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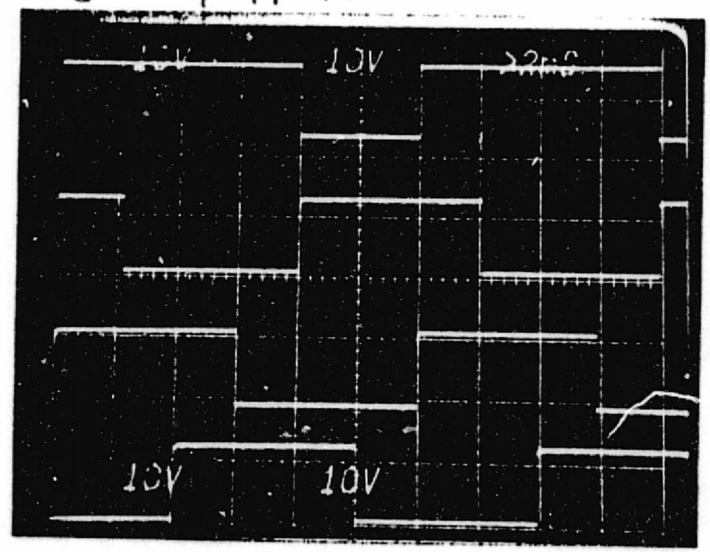

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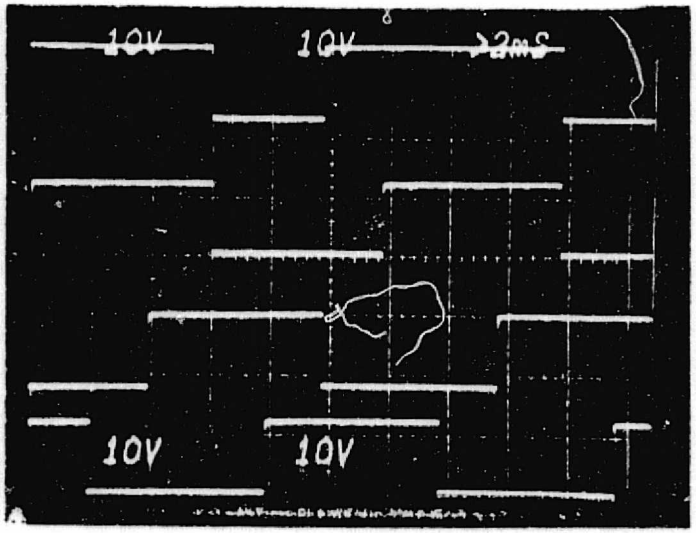
QANON
C3-13

A
E17-15

B
E2-1

C
E3-1



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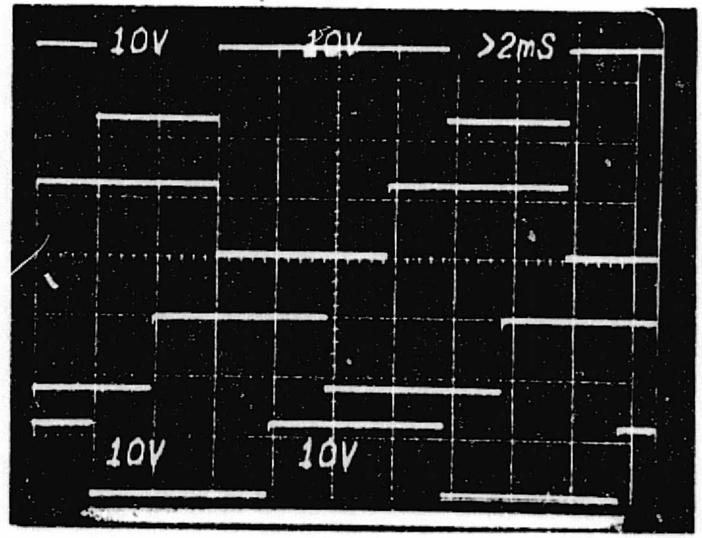

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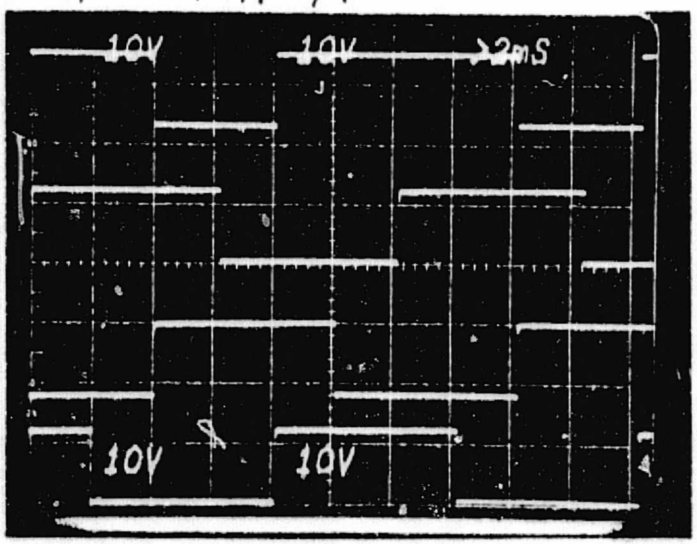
QBPON
C4-4

A
E17-15

B
E2-1

C
E3-1



12 7-14-77

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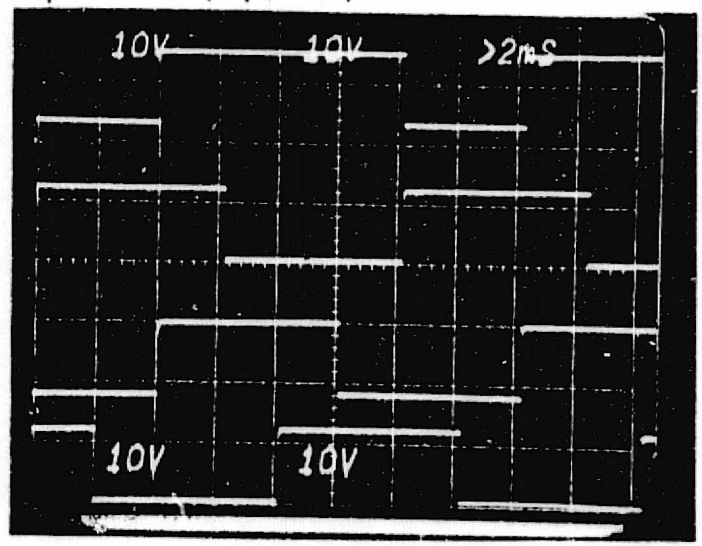

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13 7-14-77

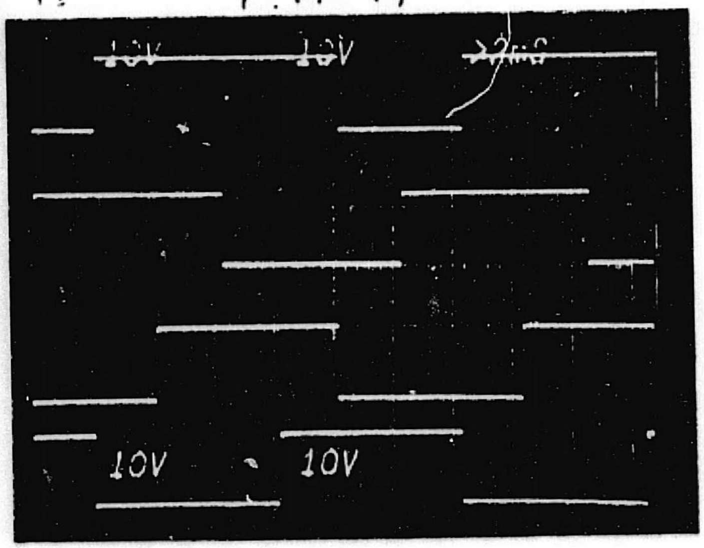
F=1

$\overline{QBNON}$
C4-13

A
E17-15

B
E2-1

C
E3-1



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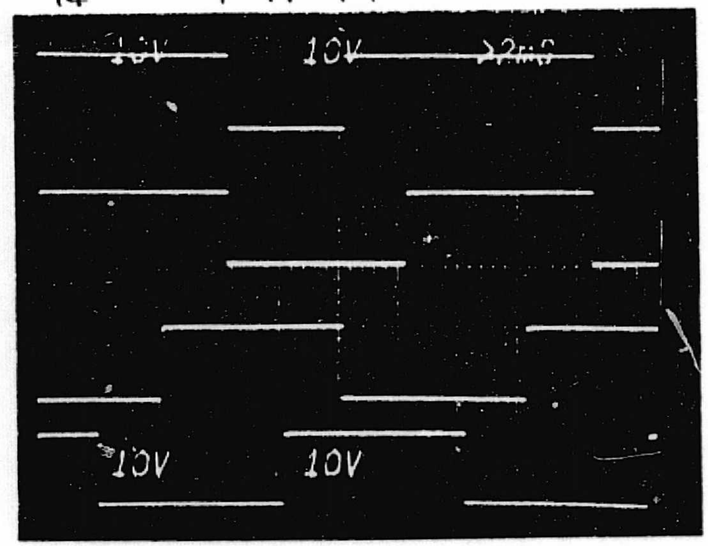


15 7-14-77

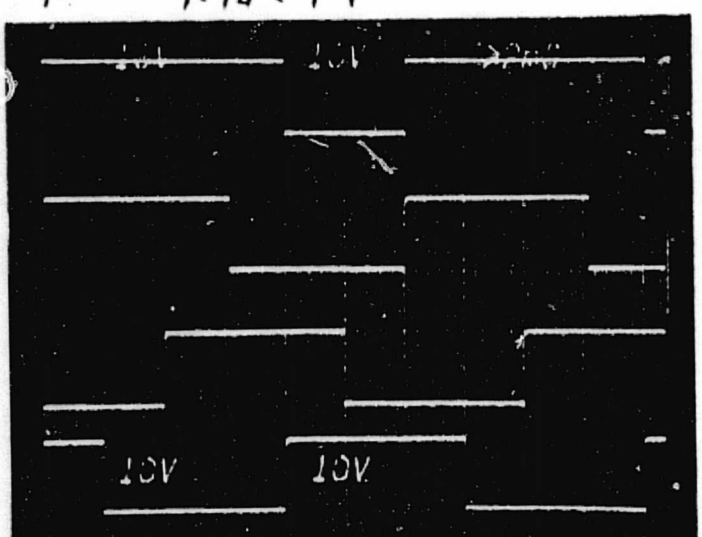
F=1

$\overline{QCPON}$
C20-4

A
E17-15

B
E2-1

C
E3-1



16 7-14-77

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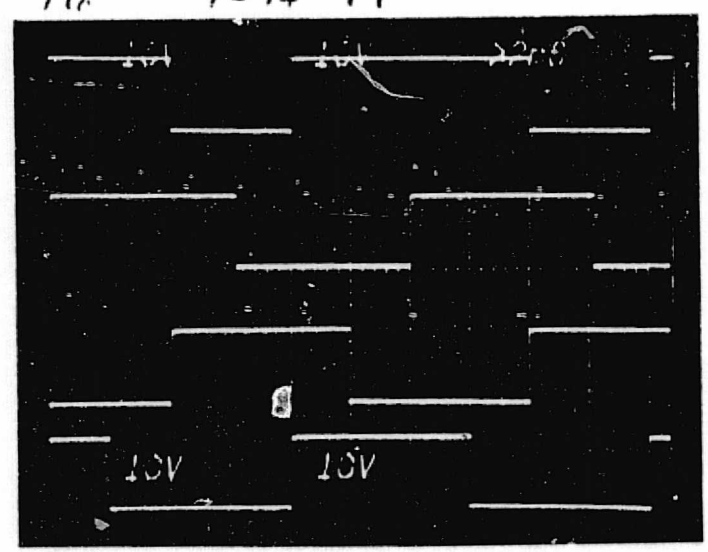

17 7-14-77

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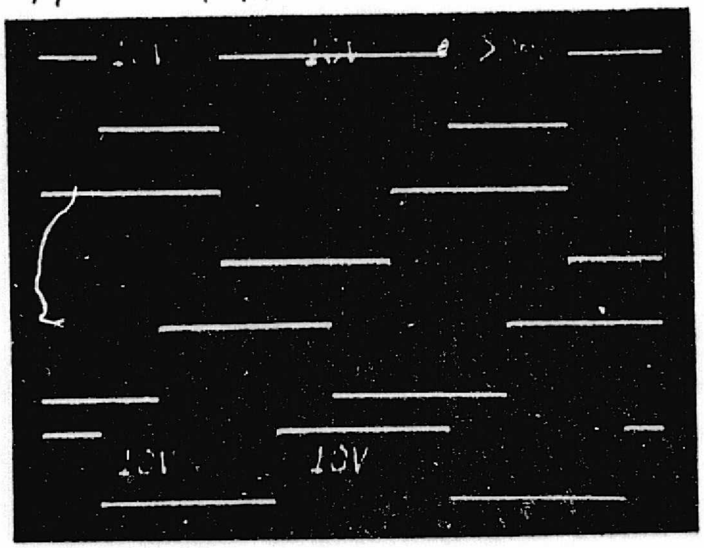
QCNON C20-13

A E17-15

B E2-1

C E3-1



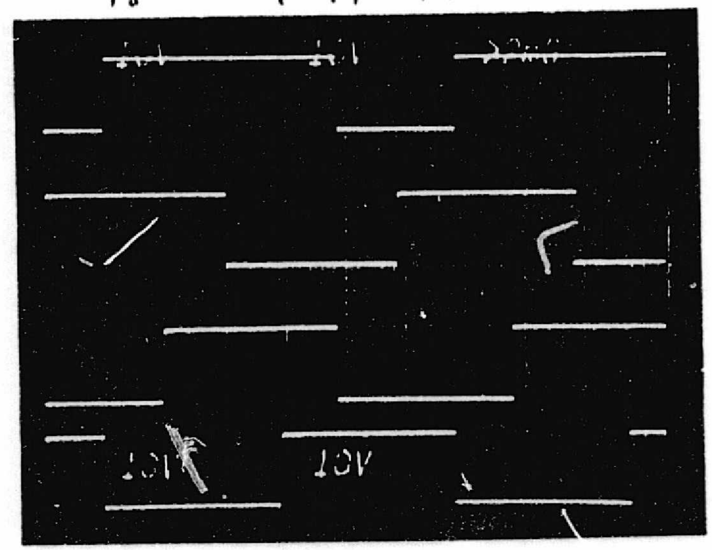
18 7-14-77

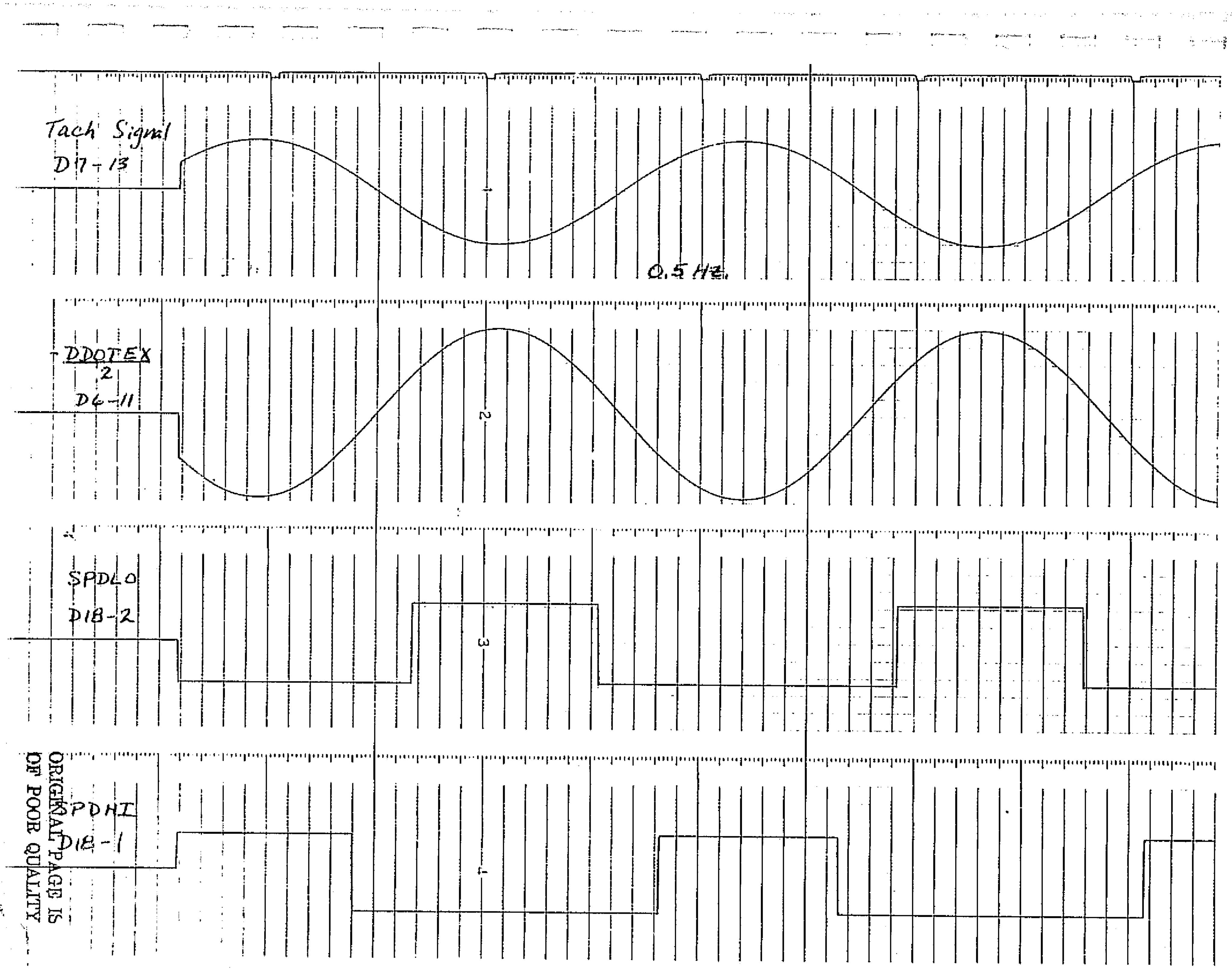
F=0

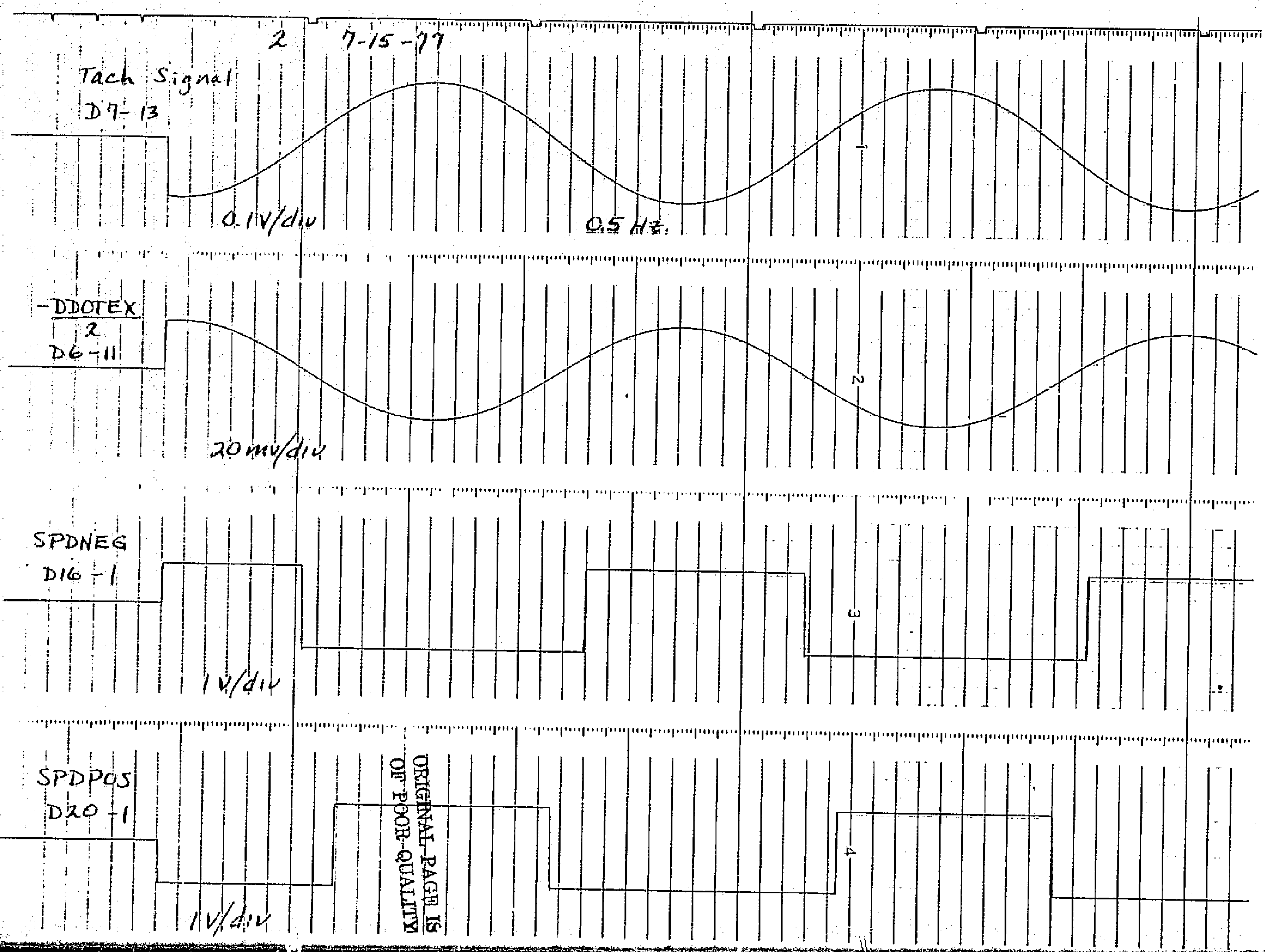
A

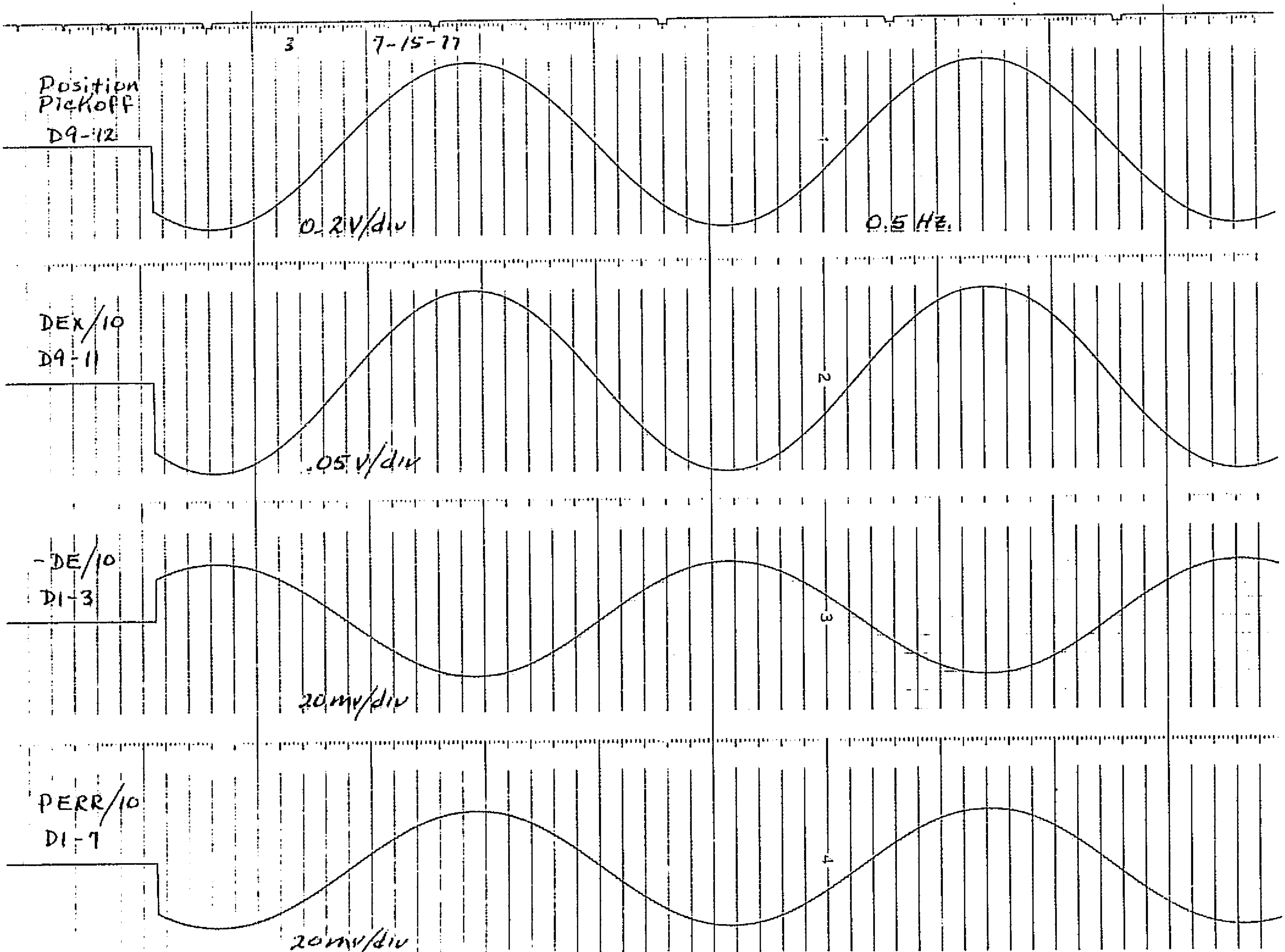
B

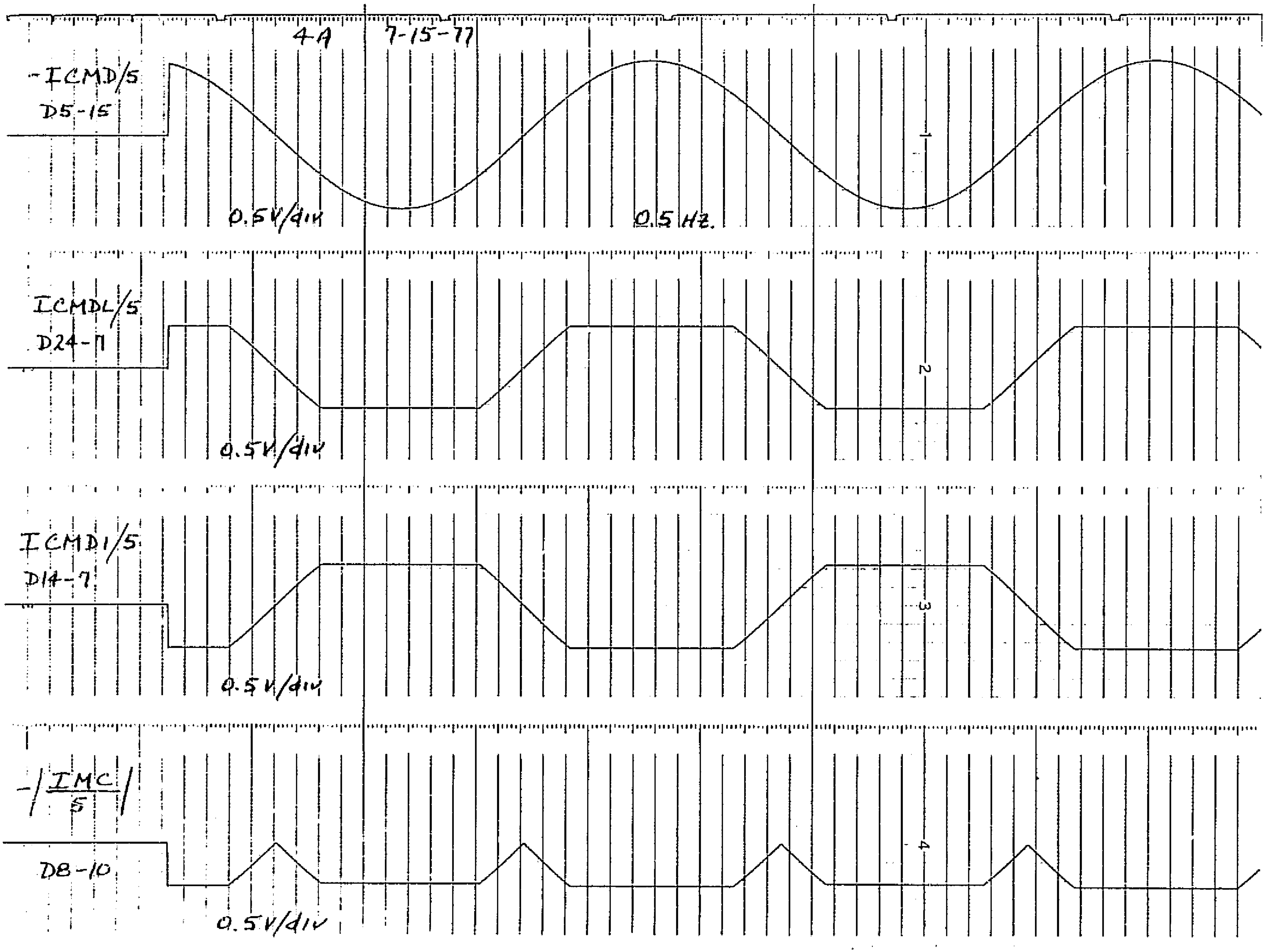
C



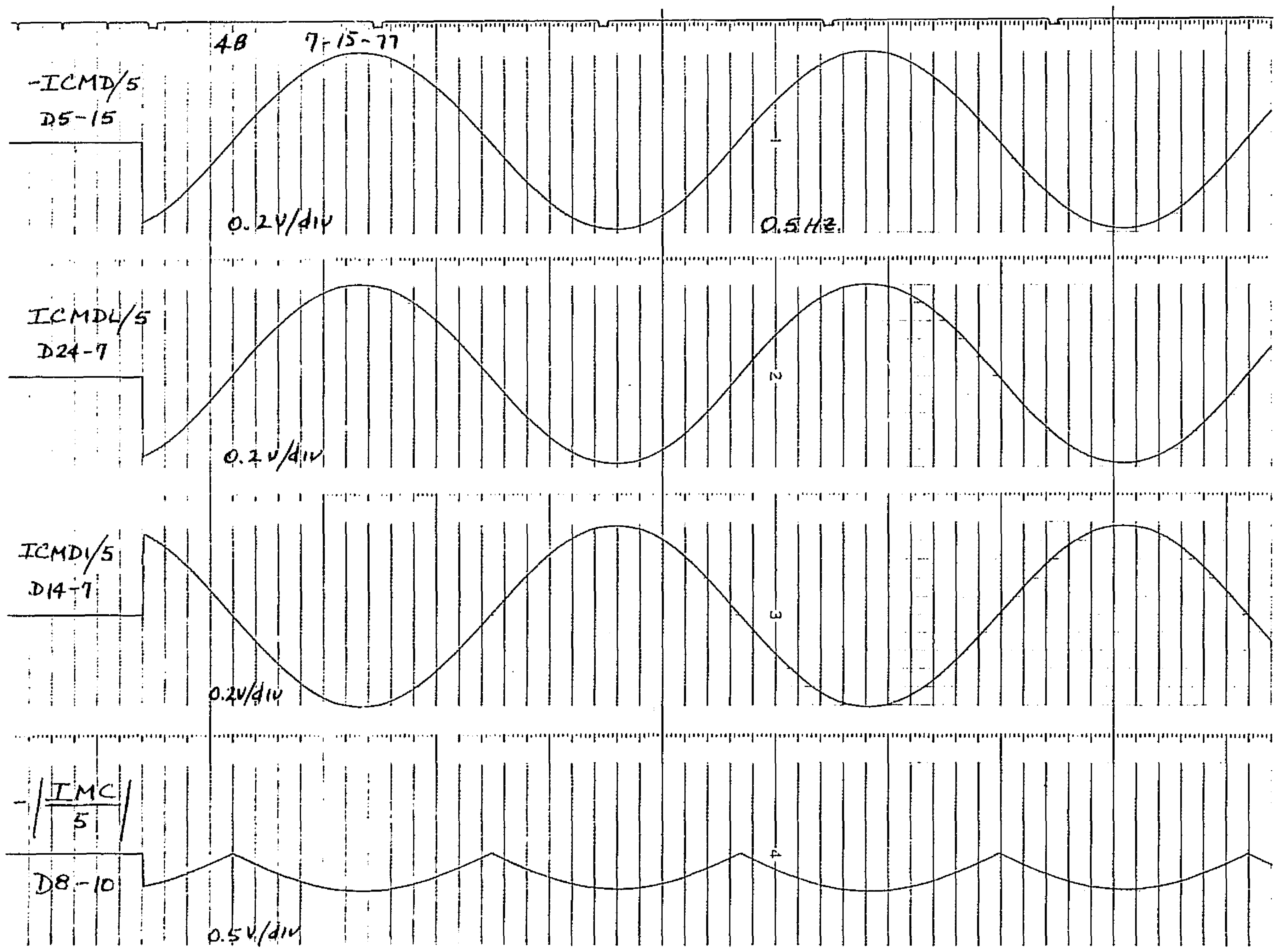

Tach Signal
D17-13
0.5 Hz.
-DDOTEX
2
D6-11
SPDLO
D18-2
SPDHI
D18-1
1
2
3
4


2
7-15-77
Tach Signal
D7-13
0.1V/div
0.5 Hz.
1
-DDOTEX
2
D6-11
20mv/div
2
SPDNEG
D16-1
1V/div
3
SPDPOS
D20-1
1V/div
4

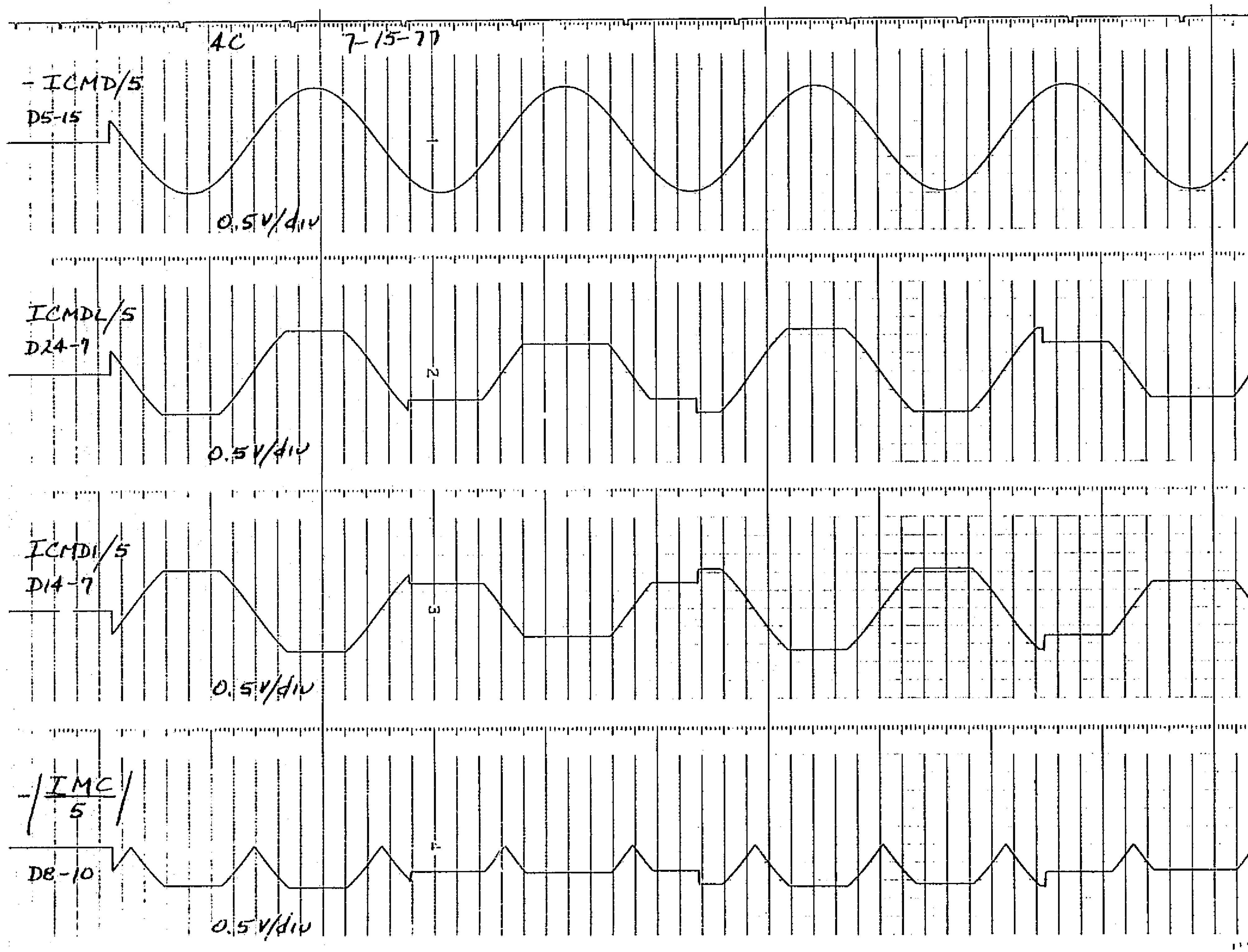

3
7-15-77
Position Pickoff
D9-12
0.2V/div
0.5 Hz.
DEX/10
D9-11
.05V/div
-DE/10
D1-3
20mv/div
PERR/10
D1-7
20mv/div

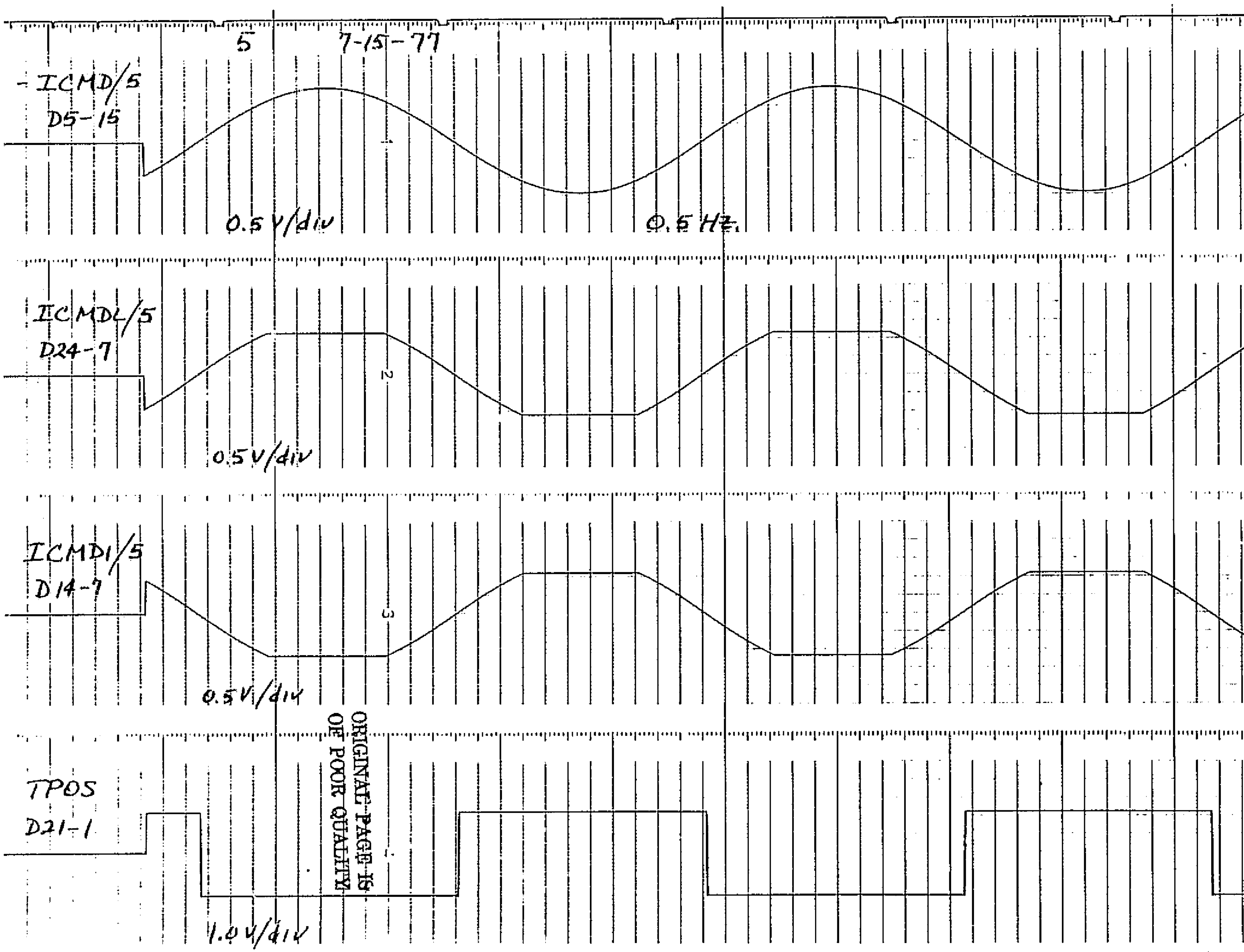


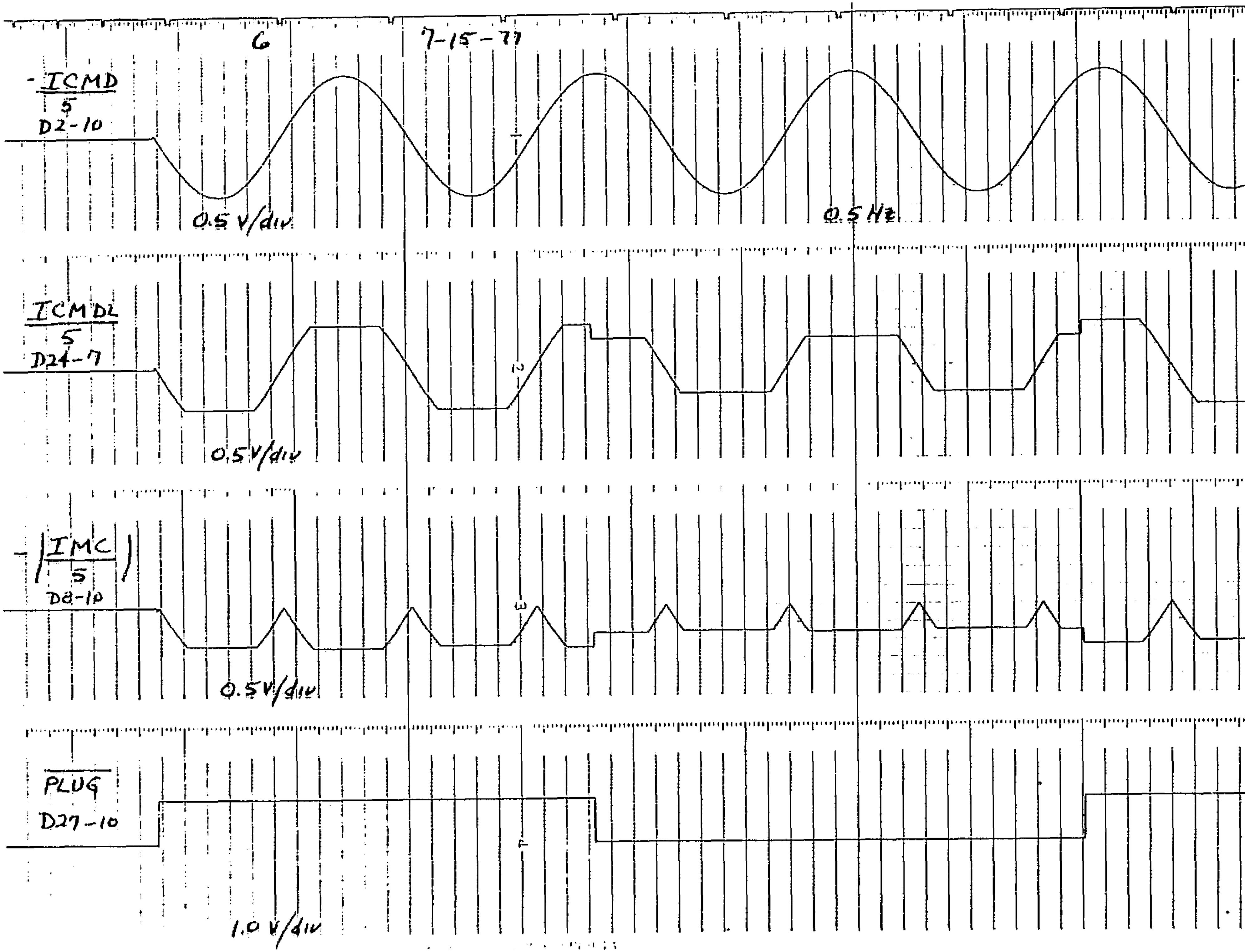
4A
7-15-77
-ICMD/5
D5-15
0.5V/div
0.5 Hz.
ICMDL/5
D24-7
0.5V/div
ICMDI/5
D14-7
0.5V/div
-|IMC/5|
D8-10
0.5V/div



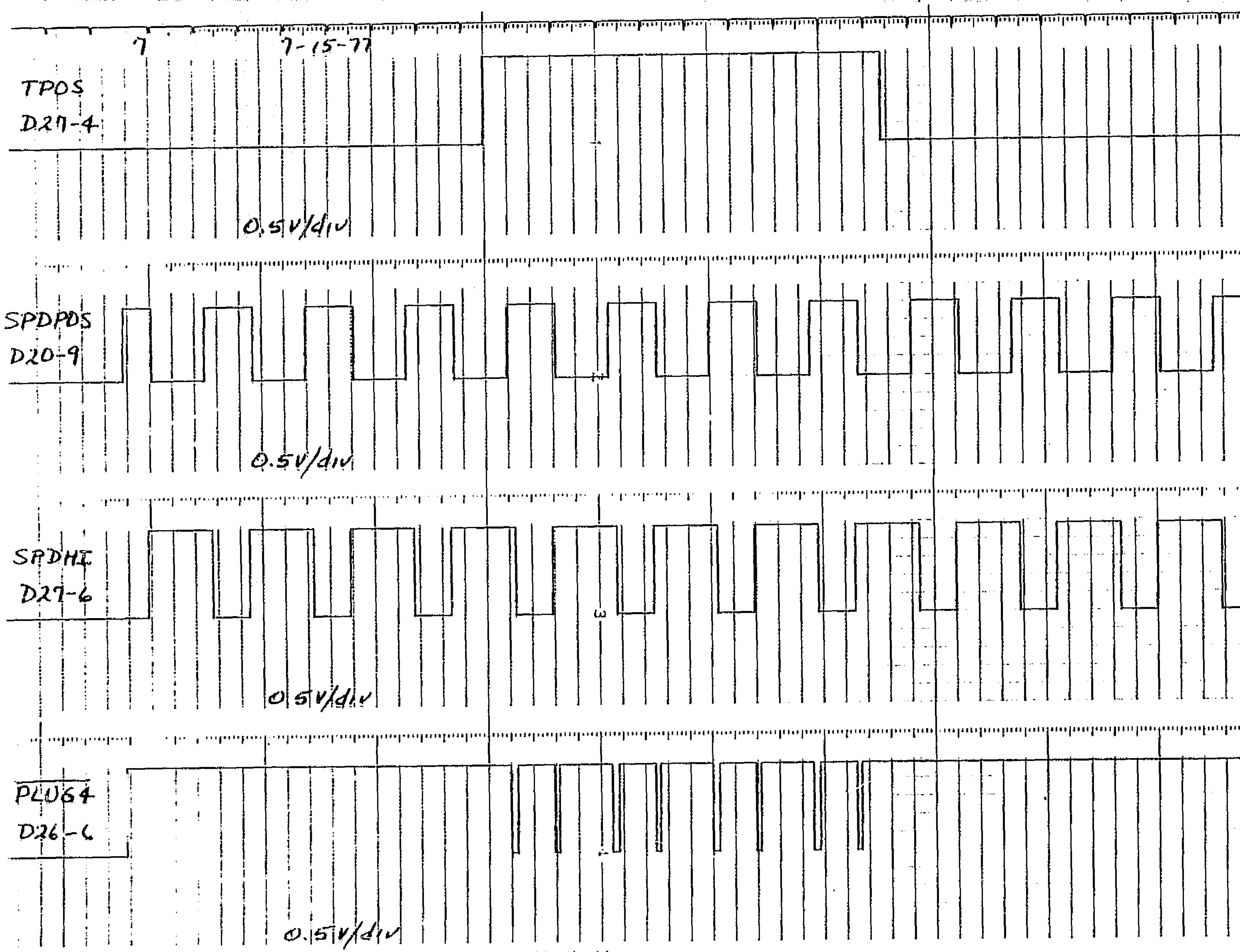
4B
7-15-77
-ICMD/5
D5-15
0.2V/div
0.5Hz
ICMDL/5
D24-7
0.2V/div
ICMD1/5
D14-7
0.2V/div
-|IMC/5|
D8-10
0.5V/div


4C
7-15-77
-ICMD/5
D5-15
0.5V/div
ICMDL/5
D24-7
0.5V/div
ICMDI/5
D14-7
0.5V/div
-|IMC/5|
D8-10
0.5V/div

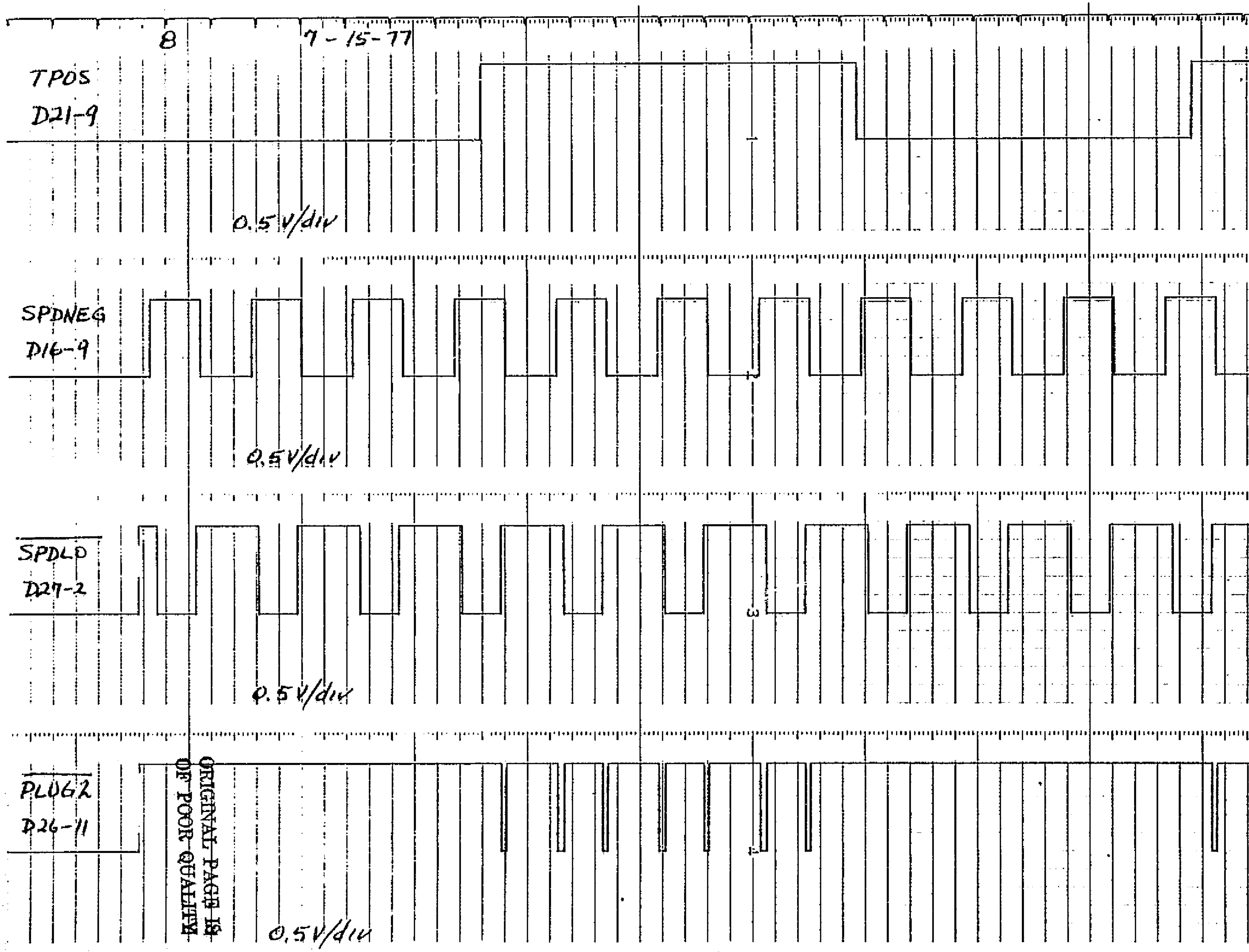

5
7-15-77
-ICMD/5
D5-15
0.5 V/div
0.5 Hz.
ICMDL/5
D24-7
0.5 V/div
ICMDI/5
D14-7
0.5 V/div
TPOS
D21-1
1.0 V/div

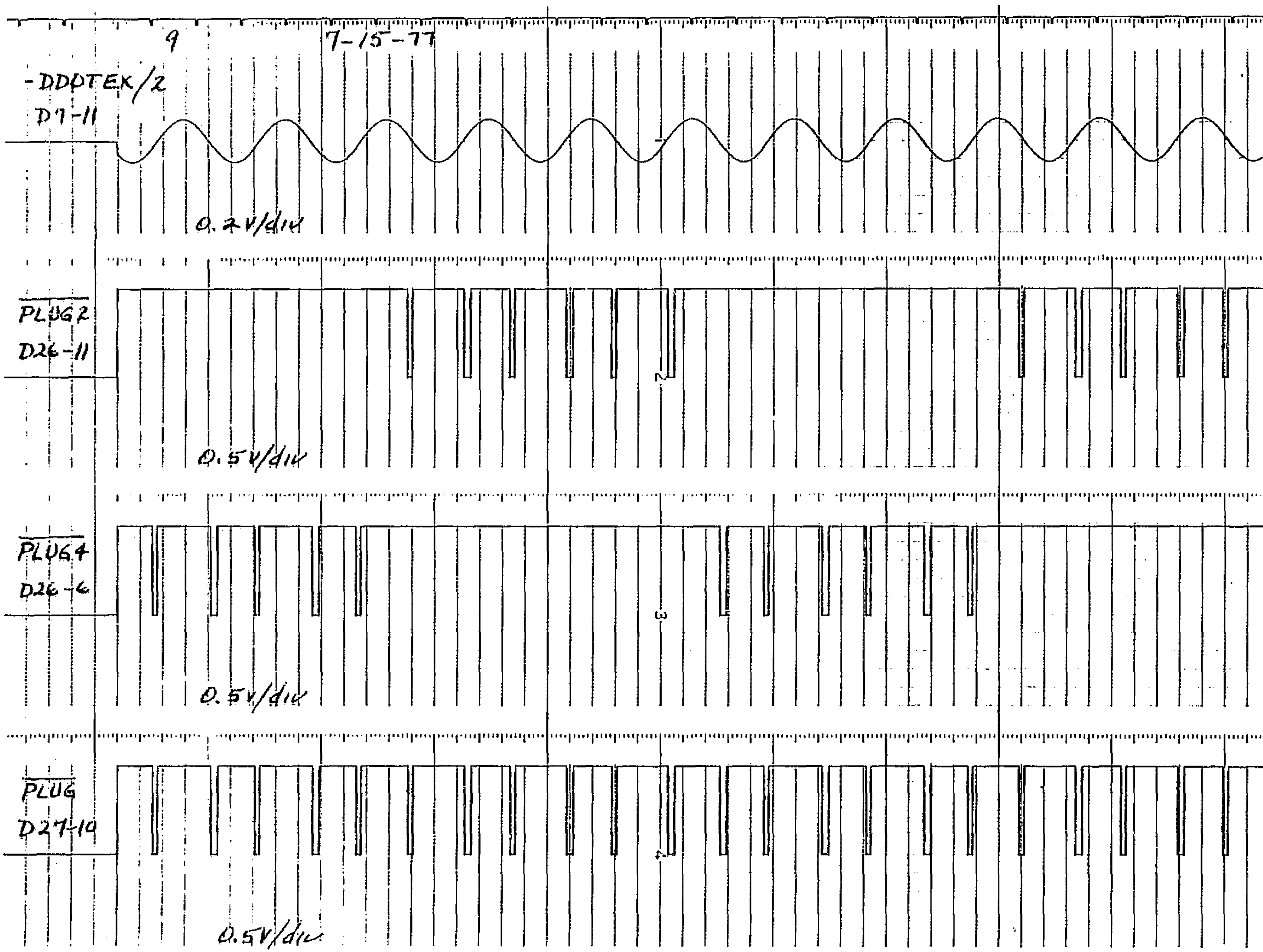


6
7-15-77
$-\frac{ICMD}{5}$
D2-10
0.5 V/div
0.5 Hz
$\frac{ICMD2}{5}$
D24-7
0.5V/div
$-\left|\frac{IMC}{5}\right|$
D8-10
0.5V/div
$\overline{PLUG}$
D27-10
1.0 V/div



7
7-15-77
TPOS
D27-4
0.5V/div
SPDPOS
D20-9
0.5V/div
SPDHI
D27-6
0.5V/div
PLUG4
D26-6
0.5V/div


8
7-15-77
TPOS
D21-9
0.5V/div
SPDNEG
D16-9
0.5V/div
SPDLD
D27-2
0.5V/div
PLUG2
D26-11
0.5V/div

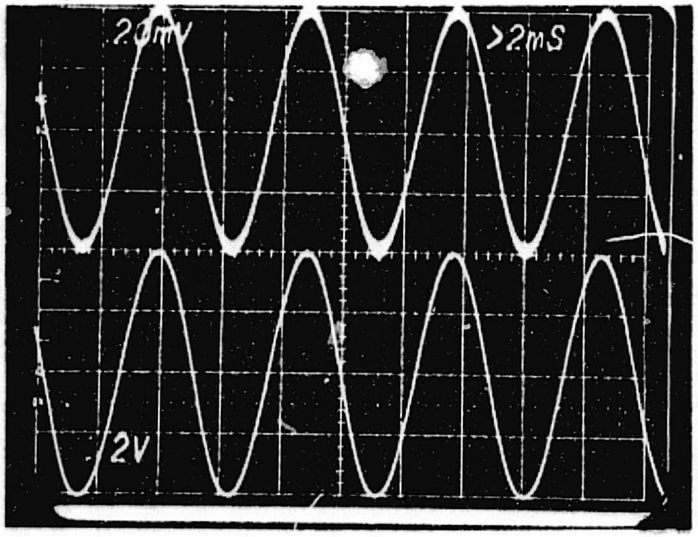

9
7-15-77
-DDDTEK/2
D7-11
0.2V/div
PLUG2
D26-11
0.5V/div
PLUG4
D26-6
0.5V/div
PLUG
D27-10
0.5V/div

10 7-15-77

200 Hz.

CUR INPUT

IM/10 B9-14

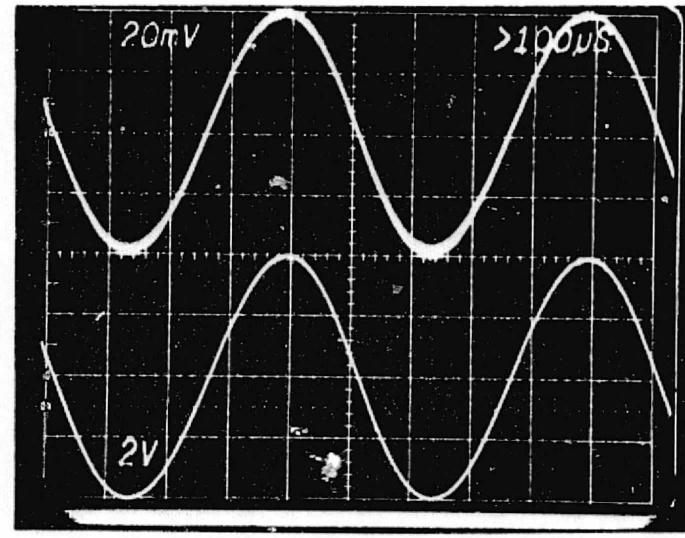


11 7-15-77

2000Hz.

CUR INPUT

IM/10 B9-14

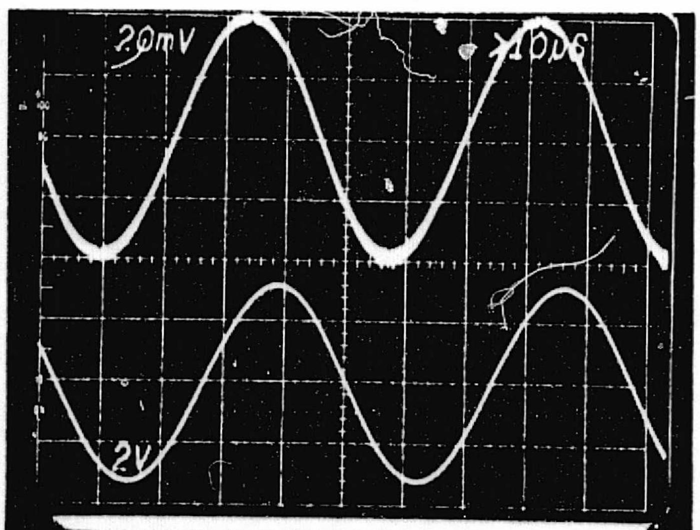


12 7-15-77

20KHz.

CUR INPUT

IM/10 B9-14

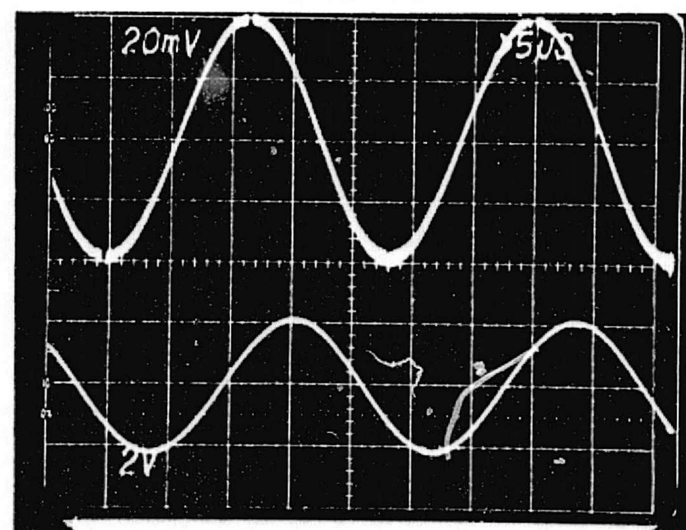


13 7-15-77

40KHz.

CUR INPUT

IM/10 B9-14



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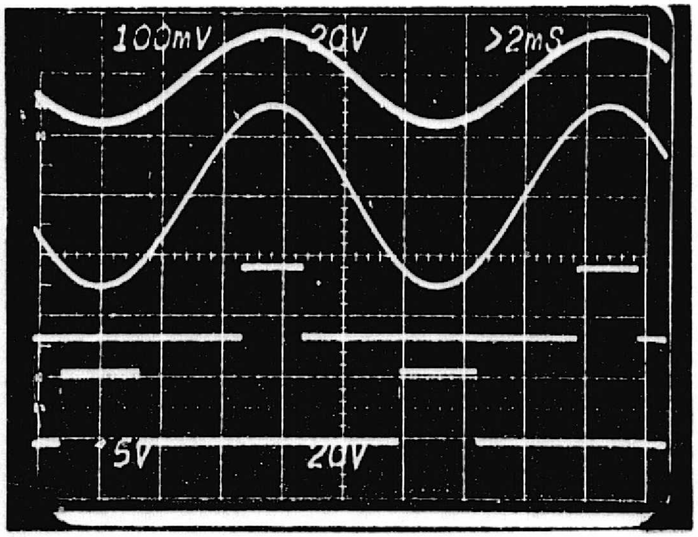
14 1-15-77

CUR INPUT

IM/10 B9-14

IMHI B6-1

IMLO B14-1



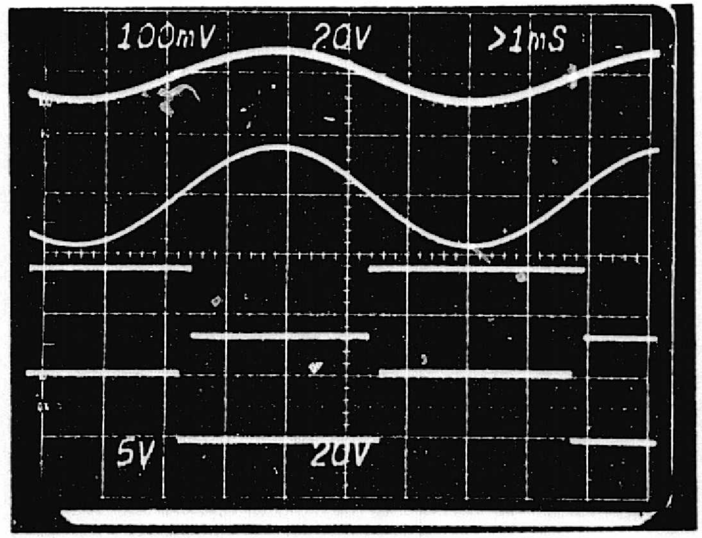
15 1-15-77

CUR INPUT

IM/10 B9-14

QMC B2-1

$\overline{QBC}$ B4-1



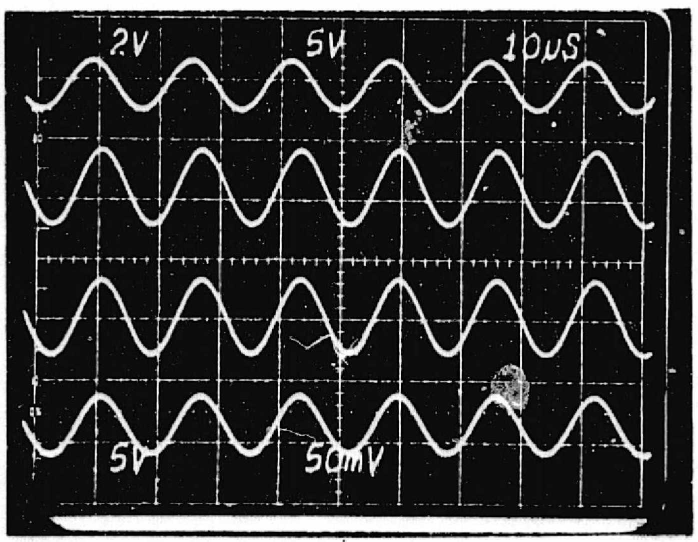
16 1-15-77 67.5K HZ.

67.5KHZ COMMON MODE VOLTAGE

AMPL IN+ B-J2-11

AMPL IN - B-J2-12

IM/10 B9-13



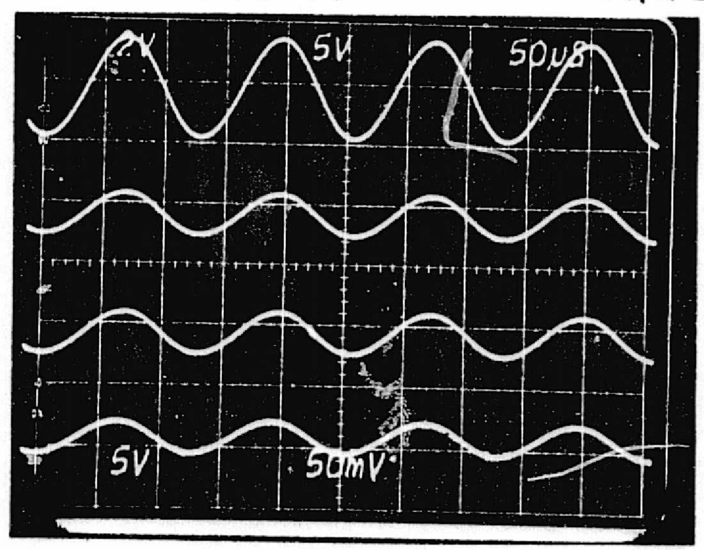
17 1-15-77 10KHZ.

10KHZ. COMMON MODE VOLTAGE

AMPL IN+ B-J2-11

AMPL IN - B-J2-12

IM/10 B9-13



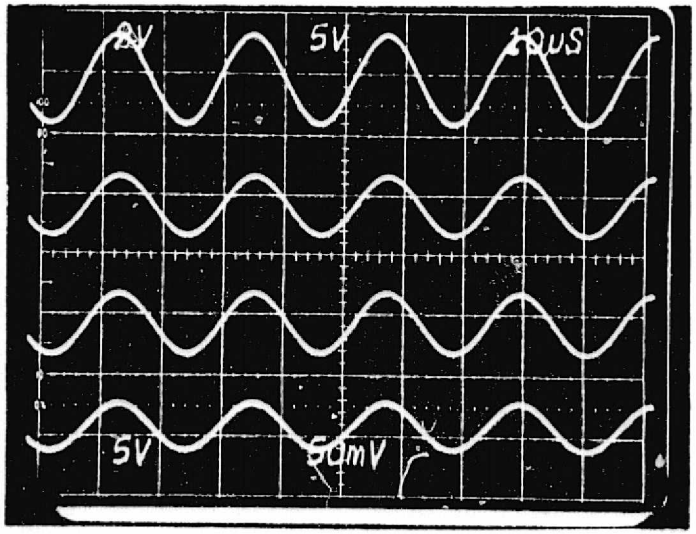
18 1-15-77 50KHZ

50KHZ
COMMON
MODE
VOLTAGE

AMPL IN +
B-J2-11

AMPL IN -
B-J2-12

IM/10
B9-13



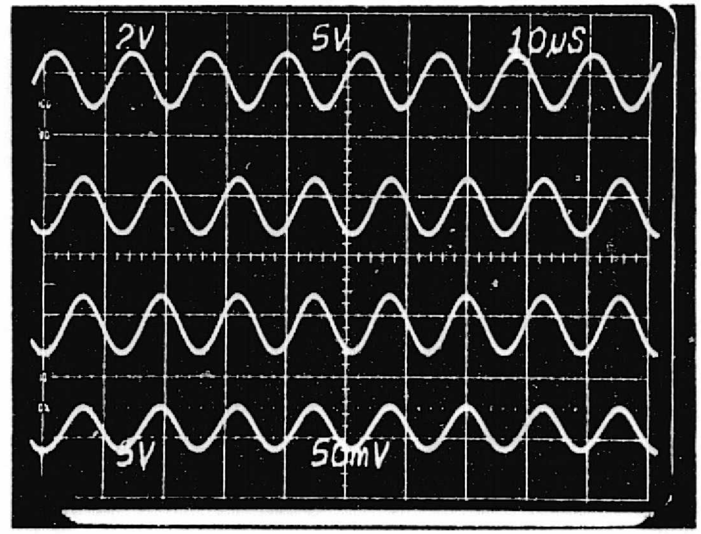
19 1-15-77 100KHZ.

100KHZ.
COMMON
MODE
VOLTAGE

AMPL IN +
B-J2-11

AMPL IN -
B-J2-12

IM/10
B9-13



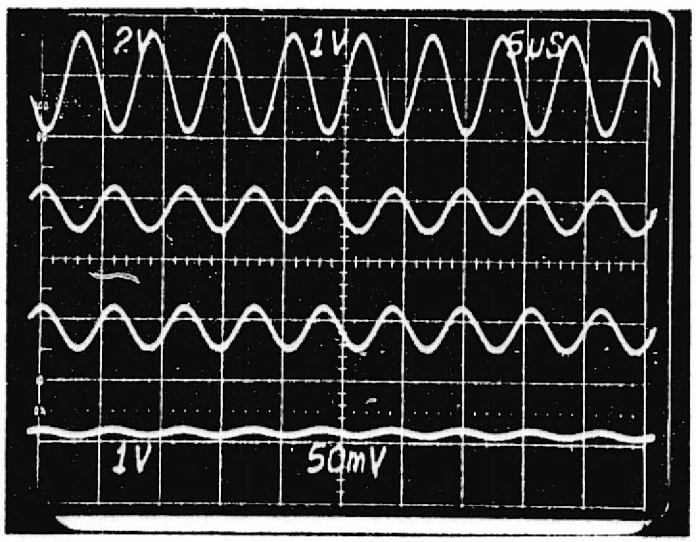
20 1-15-77 200KHZ

200KHZ.
COMMON
MODE
VOLTAGE

AMPL IN +
B-J2-11

AMPL IN -
B-J2-12

IM/10
B9-13



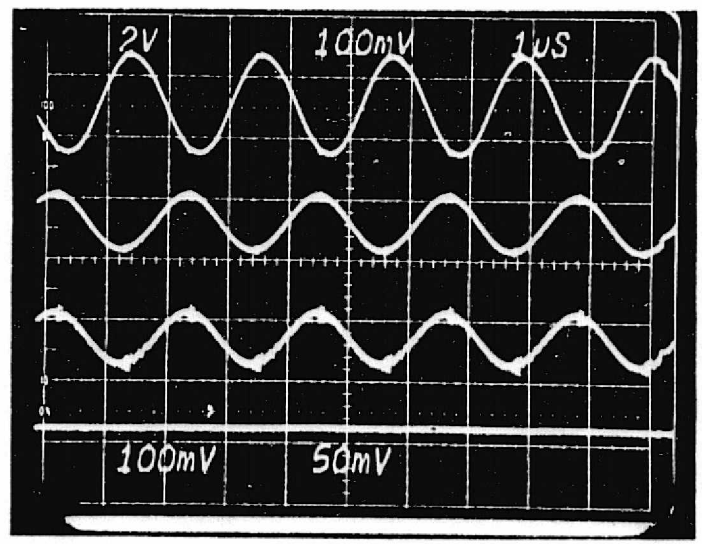
21 1-15-77 500KHZ

500KHZ.
COMMON
MODE
VOLTAGE

AMPL IN +
B-J2-11

AMPL IN -
B-J2-12

IM/10
B9-13



APPENDIX H

POWER CONVERTER WAVEFORM TESTS

The power converter waveform test results are summarized in Delco document EE-22T-EMA-019 which is incorporated in this appendix.

TITLE: Power Converter Waveform Tests

BY: A. Barrett, H. Hansen

APPROVED: H. Hansen   DATE: 12-5-77

Waveform measurements have been made of a number of voltages and currents in the power converter under various test conditions. Figure 1 is a schematic of the power converter showing the currents and voltages which were measured. Currents were measured using either T&M W-4-001 current viewing resistors or Pearson Model 110 Wideband Current Transformers. A Tektronix 7603 four-trace oscilloscope was used for the measurements.

Waveforms were recorded for various speed/torque conditions in motoring, plugging and regenerative braking modes. Table 1 lists the photo identification number for each of the runs, the variables which were recorded, the speed/torque conditions and the system operating modes. Where an external sync signal was used, it is also noted in Table 1. The positive direction for motor rotation was taken to be counterclockwise motion when viewed from the end of the motor which contains the rotor position sensor.

The waveform photographs are largely self explanatory. The scales for the vertical axes are noted near the corresponding photograph. The time scales are automatically recorded on the photographs. In photo 1, each major divison represents 500 microseconds, hence the period of the waveform is approximately

$$6 \times 500 = 3000 \text{ microseconds}$$

Therefore the motor excitation frequency is about 333 Hz. This corresponds to a speed of

$$\frac{333}{600} \times 9000 = 5000 \text{ rpm}$$

This agrees with the speed which was read out using the dynamometer instrumentation.

Readings of peak currents and voltages in the power converter were made using a peak-reading voltmeter (Memory Voltmeter Model 5201C, Micro Instrument Co.).

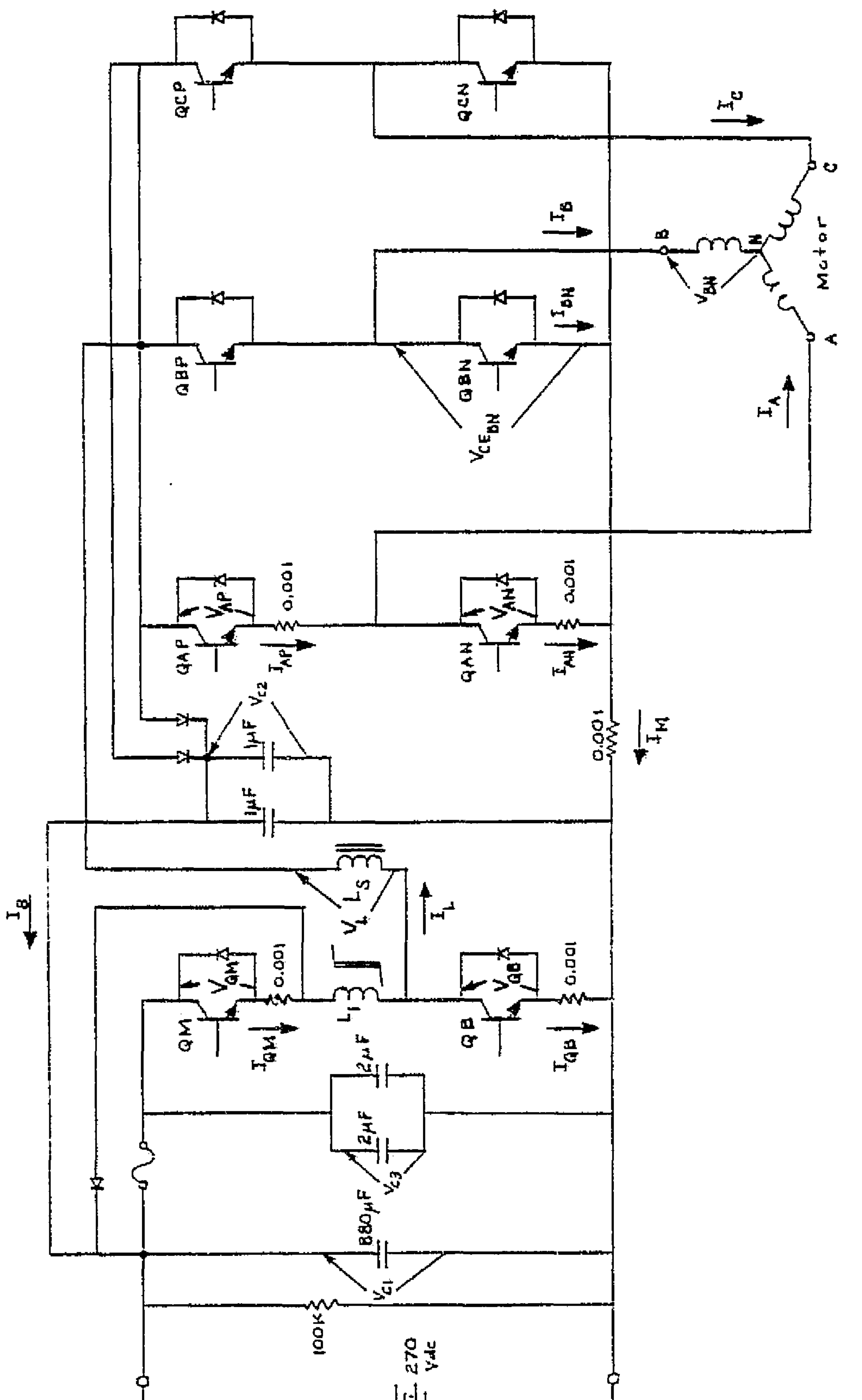


Figure 1. Power Converter Circuit

Table 1. Test Conditions

Photo Ident No.	Variables Recorded Chan 1	Chan 2	Chan 3	Torque in-lbs	Speed rpm	Operating Mode	Sync Signal
1	I_A	I_B	I_C	-63	-5000	Motoring	
2	I_A	I_B	I_C	+64	+5000	Motoring	
3	I_A	I_B	I_C	-60	+5090	Regen	
4	I_A	I_B	I_C	-71	+300	Plugging	
5	I_B	I_{BN}		-64	+240	Plugging	
6	I_B	I_{BN}		+76	-5180	Regen	
7	I_B	I_{BN}		+65	+5025	Motoring	
8	I_B	I_M		+65	+5030	Motoring	
9	I_B	I_M		+76	-5000	Regen	
10	I_B	I_M		+76	-310	Plugging	
11	I_B	I_{QB}		+65	-255	Plugging	
12	I_B	I_{QB}		+77	-5080	Regen	
13	I_B	I_{QB}		+65	+4980	Motoring	
14	I_B	I_{QM}		+65	+5050	Motoring	
15	I_B	I_{QM}		+76	-5100	Regen	
16	I_B	I_{QM}		+68	-273	Plugging	
17	I_B	I_L		+65	-245	Plugging	
18	I_B	I_L		+76	-5055	Regen	
19	I_B	I_L		+68	+5000	Motoring	
20	I_B	$V_{CE_{BN}}$		+68	+5000	Motoring	
21	I_B	$V_{CE_{BN}}$		+76	-5084	Regen	
22	I_B	$V_{CE_{BN}}$		+65	-268	Plugging	
23	I_B	V_{C2}		+68	+5050	Motoring	
24	I_B	V_{C2}		+76	-5080	Regen	
25	I_B	V_{C2}		+65	-260	Plugging	
26	I_B	V_{C3}		+68	-255	Plugging	
27	I_B	V_{C3}		+76	-5099	Regen	

Table 1. Test Conditions (Continued)

Photo Ident No.	Variables Recorded Chan 1	Chan 2	Chan 3	Torque in-lbs	Speed rpm	Operating Mode	Sync Signal
28	I_B	V_{C3}		+68	+5084	Motoring	
29	I_B	V_{C1}		+65	+5072	Motoring	
30	I_B	V_{C1}		+76	-5103	Regen	
31	I_B	V_{C1}		+68	-275	Plugging	
32	I_B	V_{BN}		+68	-265	Plugging	
33	I_B	V_{BN}		+76	-5101	Regen	
34	I_B	V_{BN}		+66	+5098	Motoring	
35	I_M			+73	+7850	Motoring	$\overline{Q_M}$
36	I_{QM}	V_{QM}		+73	+8050	Motoring	$\overline{Q_M}$
37	I_{AN}	V_{AN}		+73	+7950	Motoring	$\overline{Q_{AN}}$
38	I_{AP}	V_{AP}		+73	+7900	Motoring	$\overline{Q_{AN}}$
39	I_M	I_8		+73	+7825	Motoring	$\overline{Q_M}$
40	I_L	V_L		+72	+7750	Motoring	$\overline{Q_{AN}}$
41	I_M			+83	+4500	Motoring	$\overline{Q_M}$
42	I_{QM}	V_{QM}		+83	+4500	Motoring	$\overline{Q_M}$
43	I_{QB}	V_{QB}		+83	+4500	Motoring	$\overline{Q_M}$
44	I_{AN}	V_{AN}		+83	+4500	Motoring	$\overline{Q_{AN}}$
45	I_{AP}	V_{AP}		+83	+4500	Motoring	$\overline{Q_{AN}}$
46	I_M	I_8		+83	+4500	Motoring	$\overline{Q_M}$
47	V_{AN}			+83	+4500	Motoring	V_{AN}
48	V_{QM}			+83	+4500	Motoring	V_{QM}
49	V_{QB}			+83	+4500	Motoring	V_{QB}
50	V_{AN}			+72	+7800	Motoring	V_{AN}

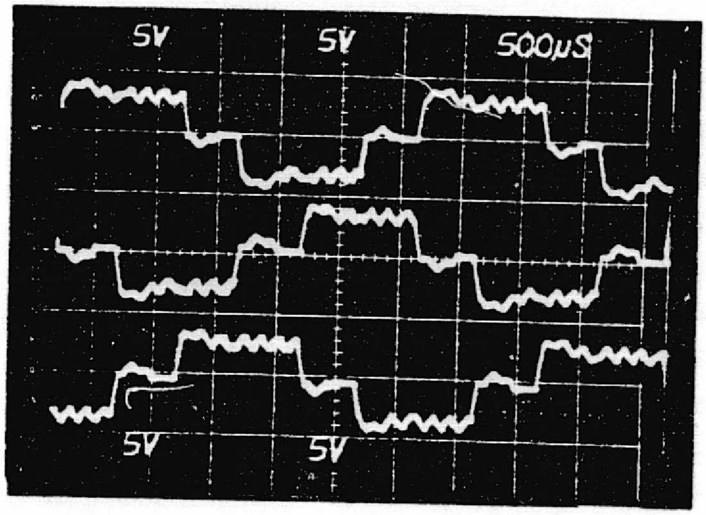
The measurements which were taken are summarized in Table 2. The peak current readings (I_{AN}, I_{AP}, I_{QM} and I_{QB}) were taken in both the forward and reverse directions, and the peak-reading voltmeter was read with response settings of both 1 and 10 microseconds. The peak collector-emitter voltages for Q_{AN}, Q_{AP}, Q_M and Q_B were also recorded. While these readings were being taken, the electromechanical actuator was being driven with a squarewave command at 0.3 Hz with $\pm$10 degree motion. During these tests, the highest operating frequency observed for Q_M was 10 kHz. The highest operating frequency for Q_B was also 10 kHz.

TRANSISTOR	MEMORY VOLTMETER RESPONSE SETTING >	PEAK REVERSE CURRENT (AMPS) 1 µs	PEAK REVERSE CURRENT (AMPS) 10 µs	PEAK FORWARD CURRENT (AMPS) 1 µs	PEAK FORWARD CURRENT (AMPS) 10 µs	PEAK COLLECTOR-EMITTER VOLTAGE 1 µs	PEAK COLLECTOR-EMITTER VOLTAGE 10 µs
Q_{AN}		46	46	64	64	320	300
Q_{AP}		46	46	64	64	320	300
Q_M		26	13	77	46	325	305
Q_B		94	60	55	48	290	290

Table 2. Peak Voltage and Current Measurements

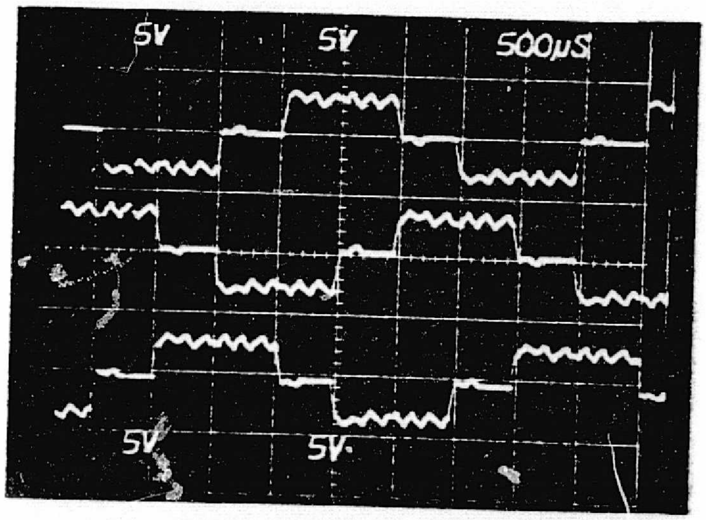
RUN

50 A/div I_A I_B I_C



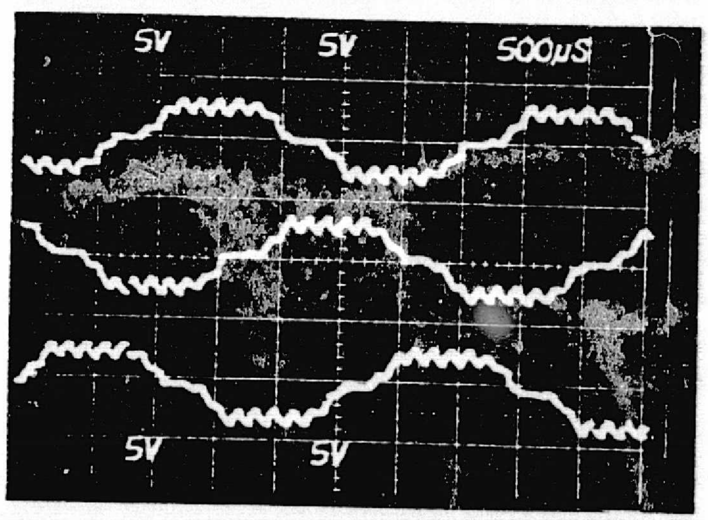
1

50 A/div I_A I_B I_C



2

50 A/div I_A I_B I_C



3

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RUN

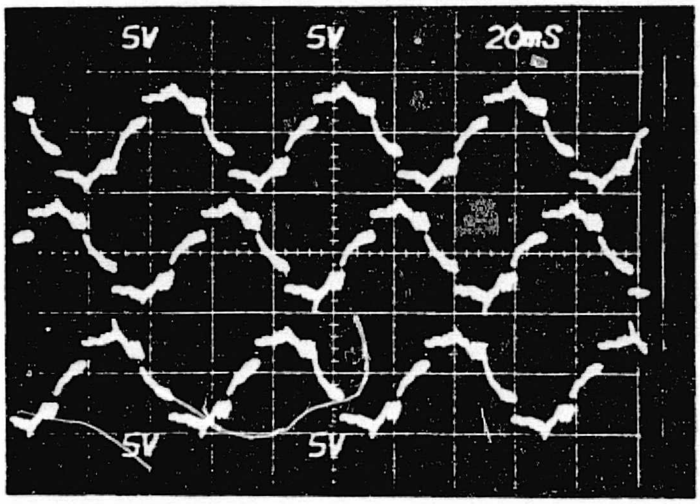
4

50 A/div

I_A

I_B

I_C

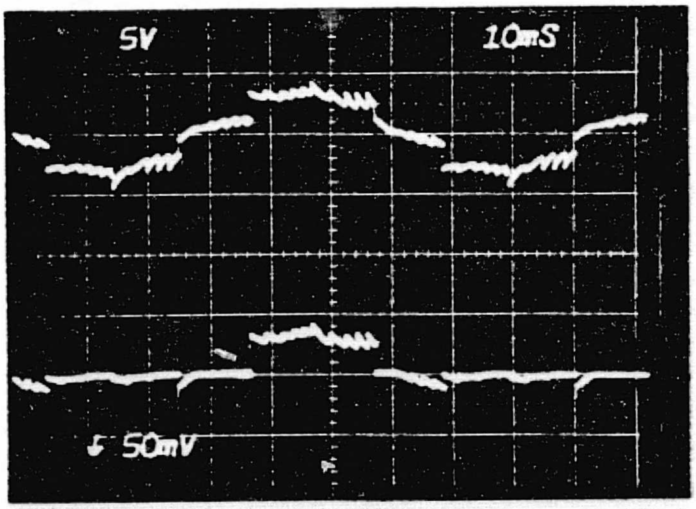


5

50 A/div

I_B

I_{BN}

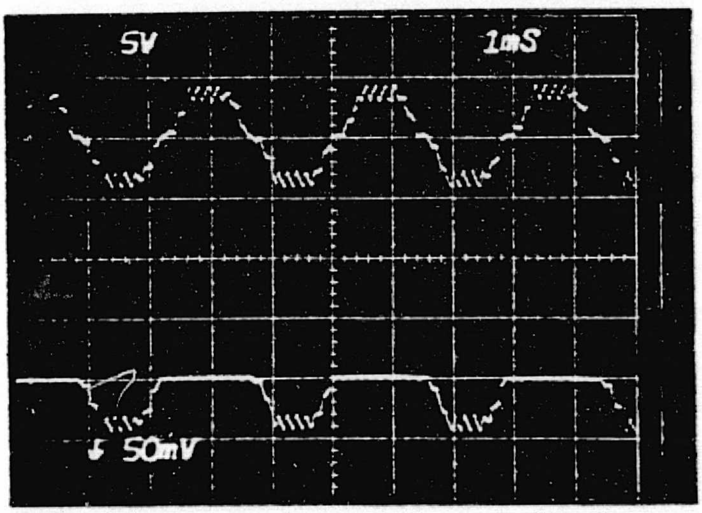


6

50 A/div

I_B

I_{BN}

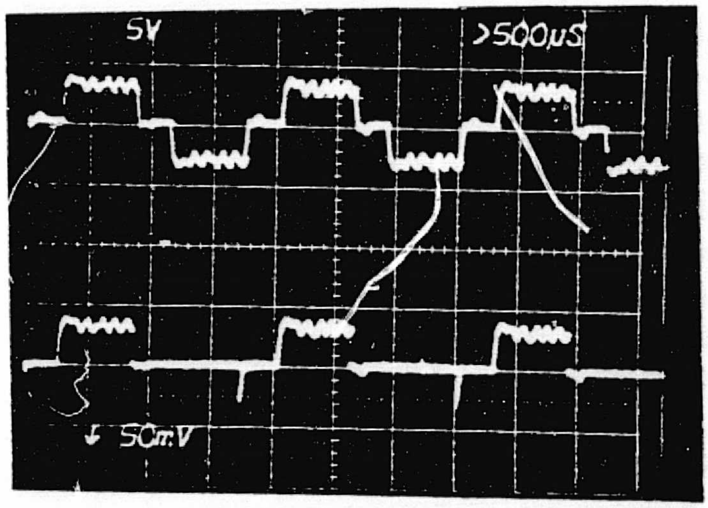


RUN

7

50 A/div I_B

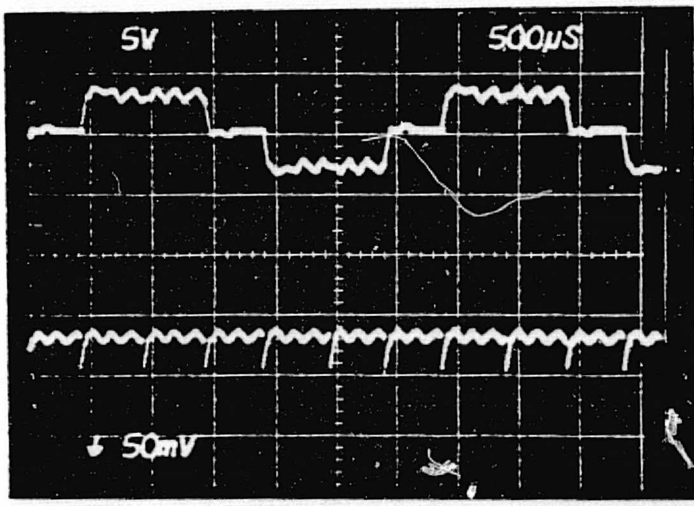
I_{BN}



8

50 A/div I_B

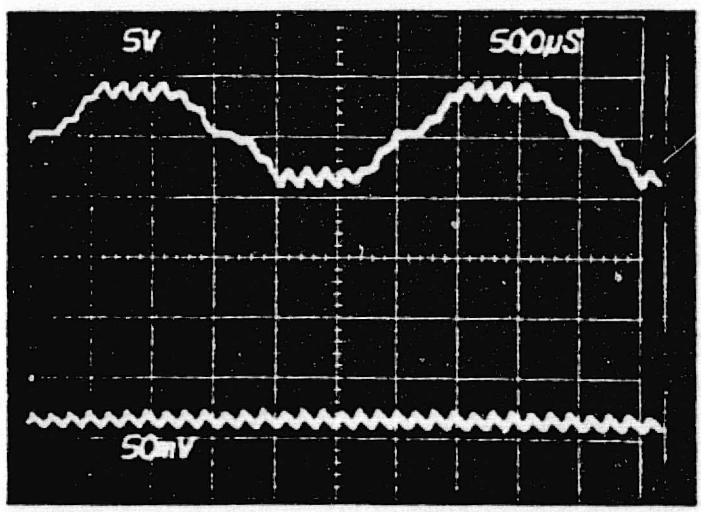
I_M



9

50 A/div I_B

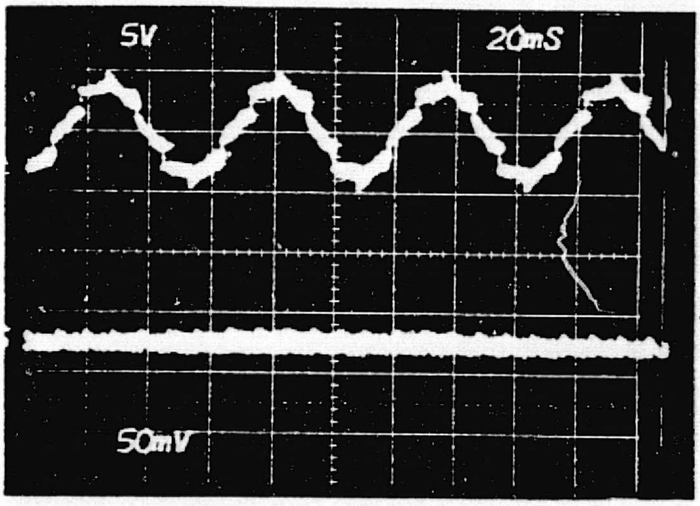
$-I_M$



RUN

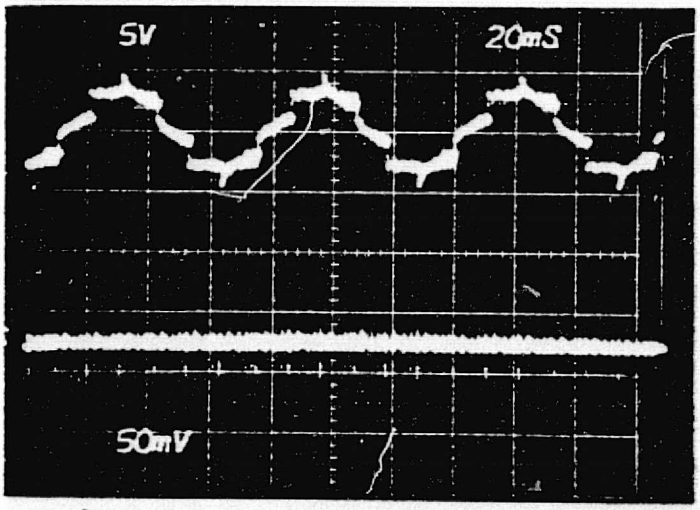
50 A/div I_B 10

$-I_M$



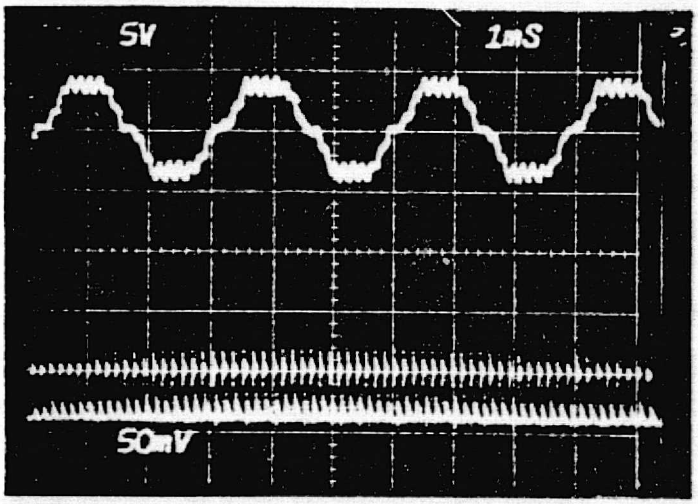
50 A/div I_B 11

I_{QB}



50 A/div I_B 12

I_{QB}



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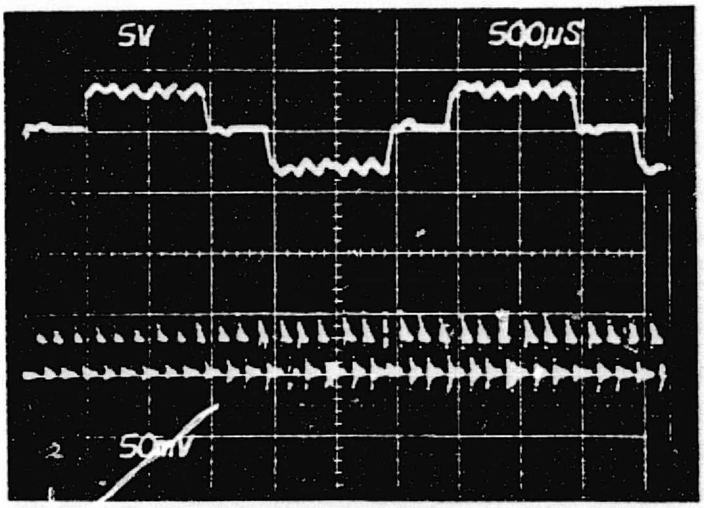
RUN

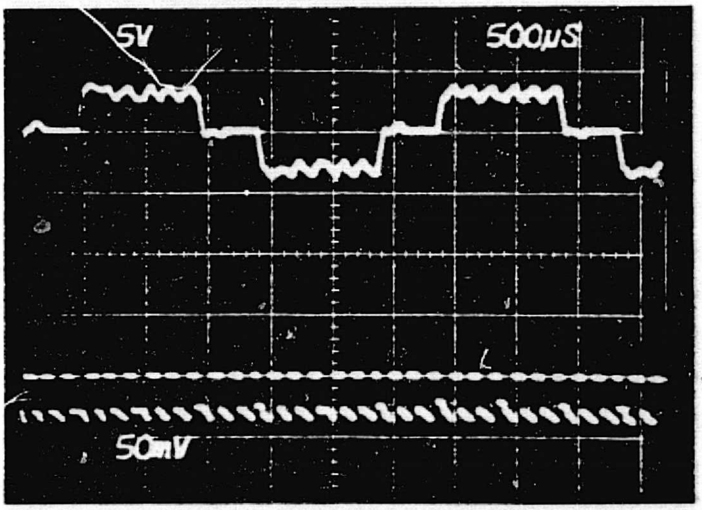
50 A/div I_B



I_{QB}

13

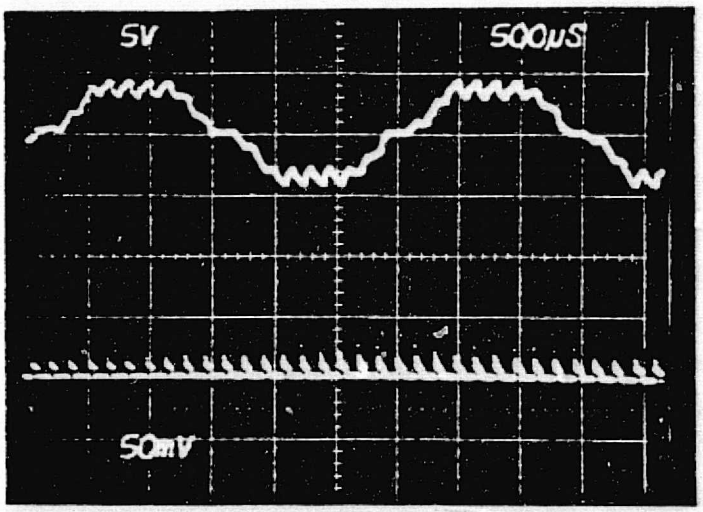
50 A/div I_B



$-I_{QM}$

14

50 A/div I_B



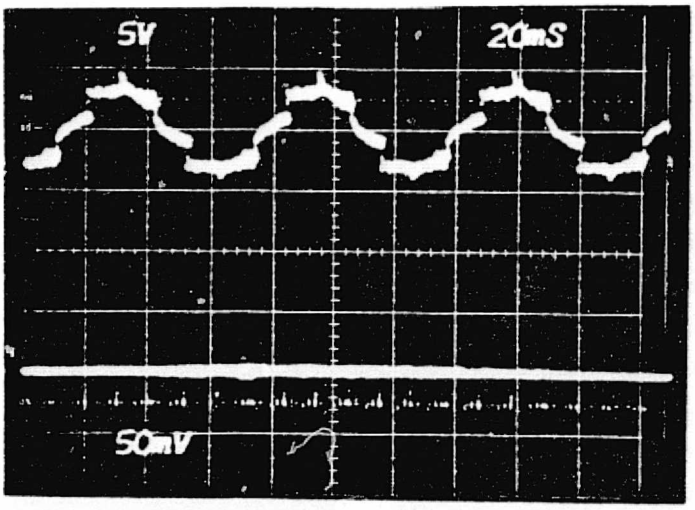
$-I_{QM}$

15

RUN 16

50 A/div I_B

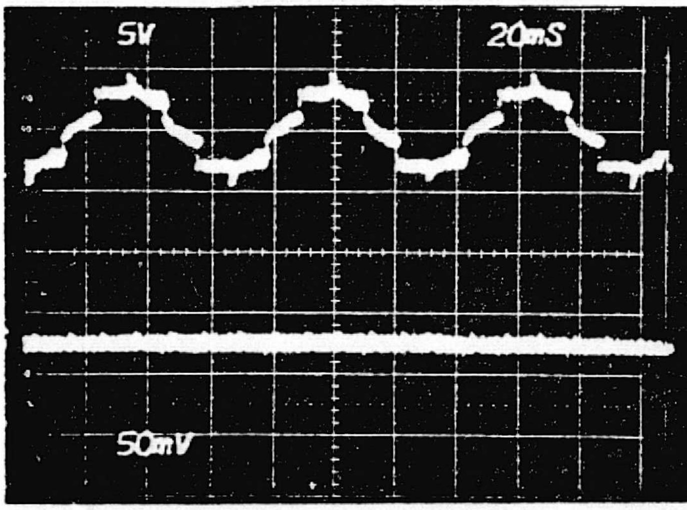
$-I_{QM}$



17

50 A/div I_B

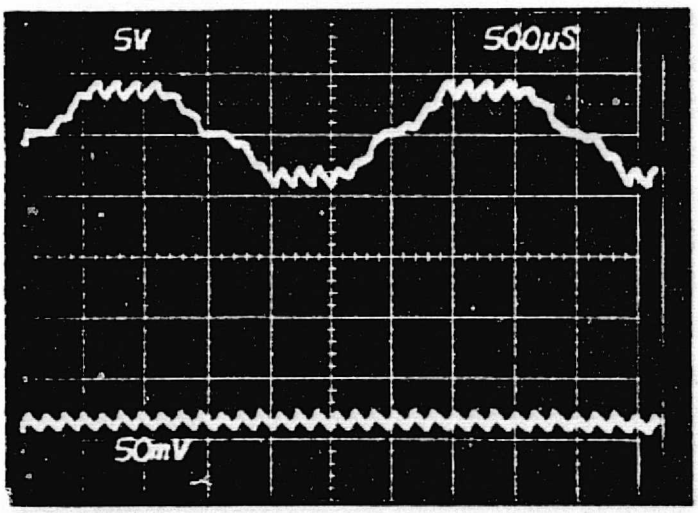
I_L



18

50 A/div I_B

I_L



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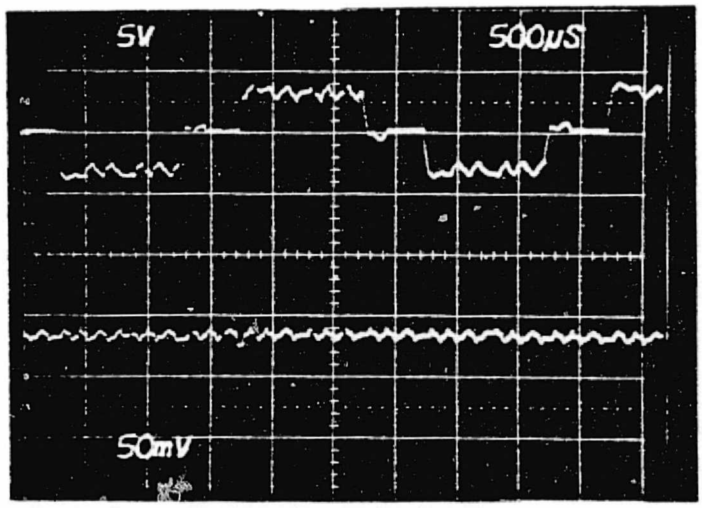
RUN

50 A/div I_B

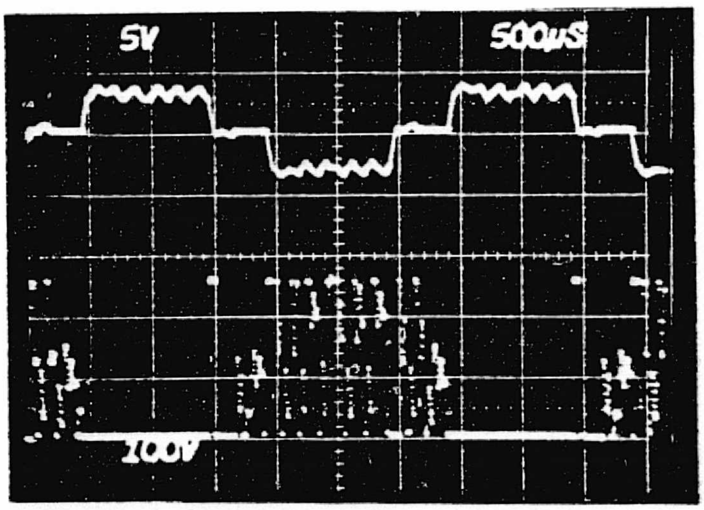
I_L



19

50 A/div I_B

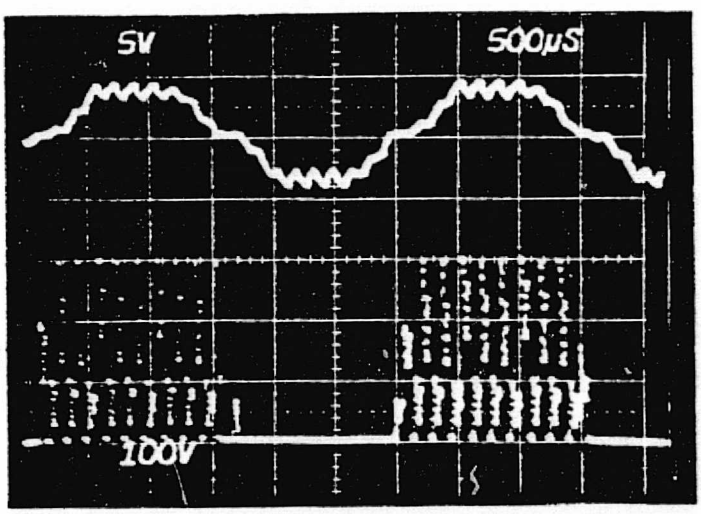
100 V/div $V_{CE_{BN}}$



20

50 A/div I_B

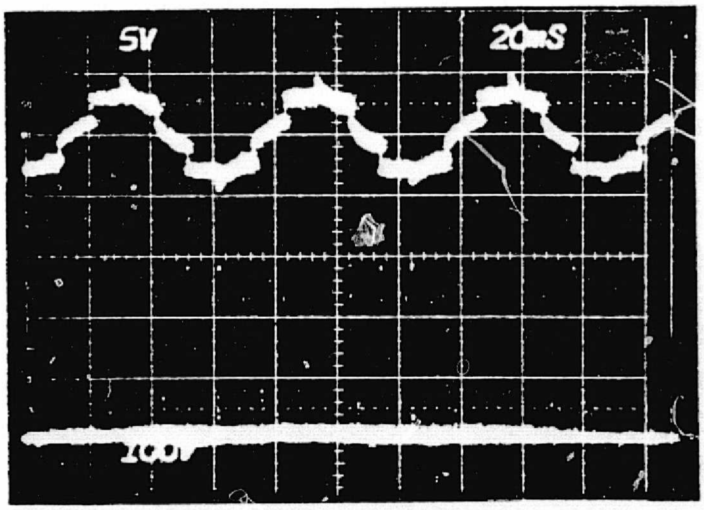
100 V/div $V_{CE_{BN}}$



21

50 A/div I_B

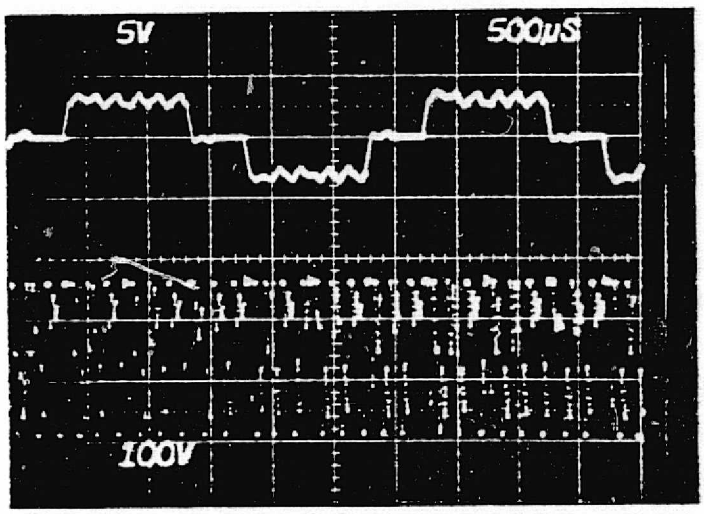
100 V/div $V_{CE_{BN}}$



RUN 22

50 A/div I_B

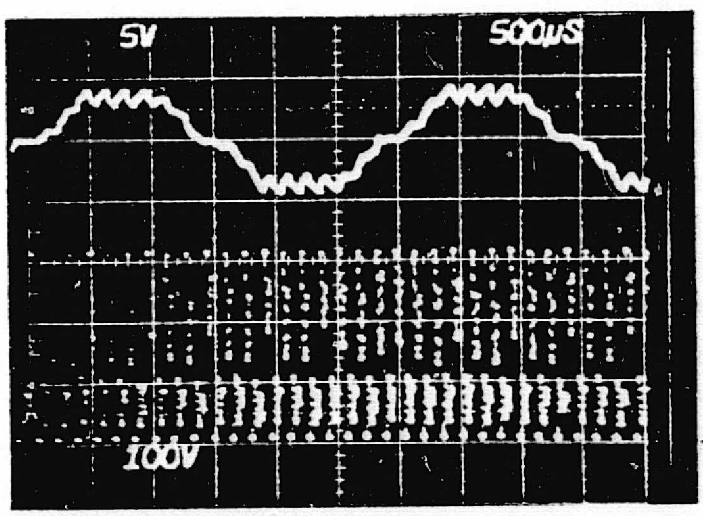
100 V/div V_{C2}



23

50 A/div I_B

100 V/div V_{C2}

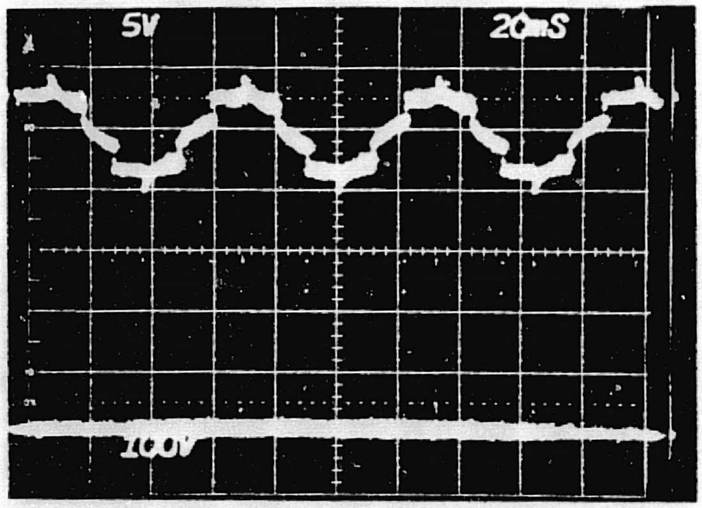


24

RUN 25

50 A/div I_B

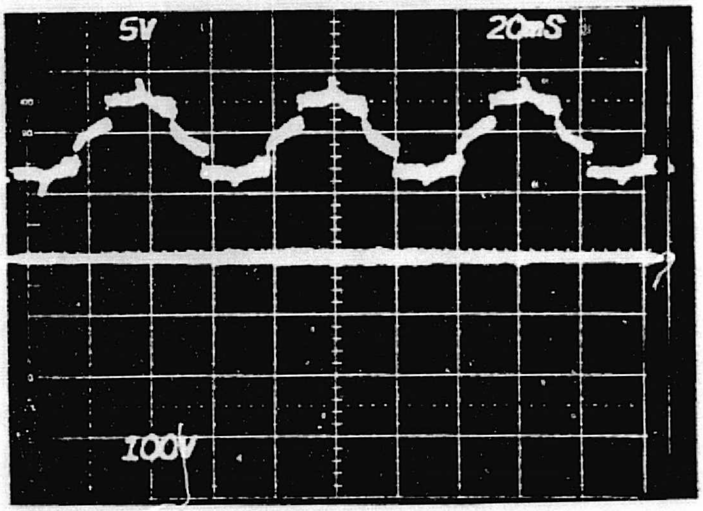
100 V/div V_{C2}



26

50 A/div I_B

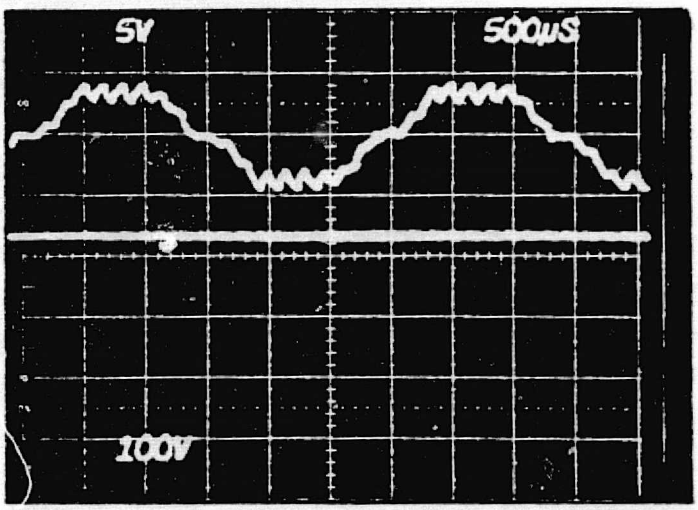
100 V/div V_{C3}



27

50 A/div I_B

100 V/div V_{C3}



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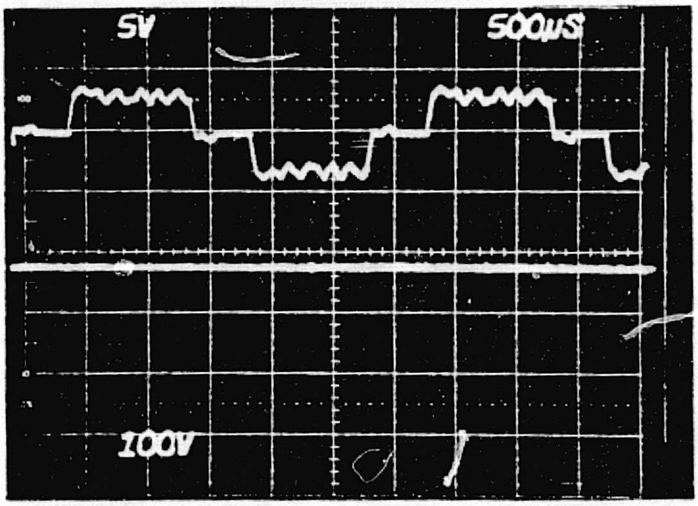
RUN

50 A/div I_B

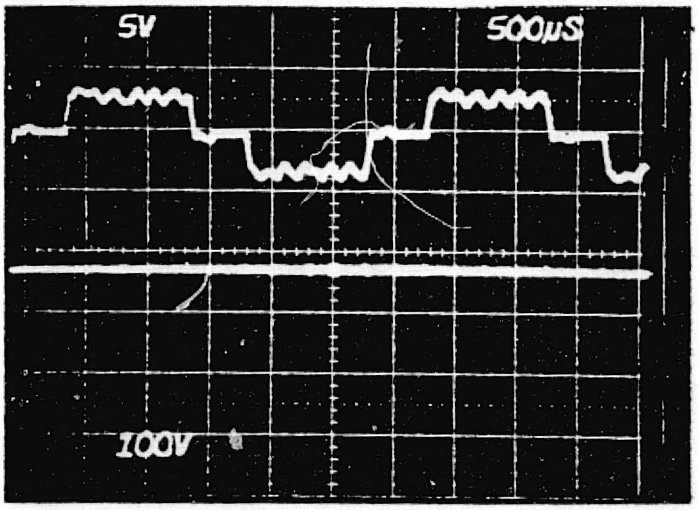
100 V/div V_{C3}



28

50 A/div I_B

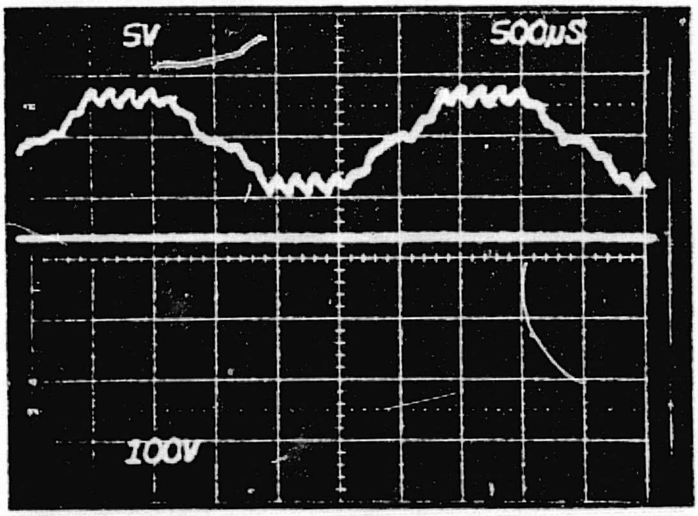
100 V/div V_{C1}



29

50 A/div I_B

100 V/div V_{C1}

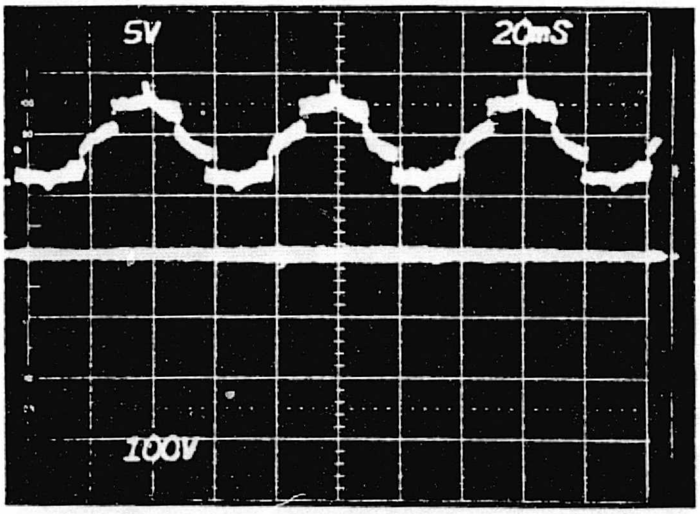


30

RUN 31

50 A/div I_B

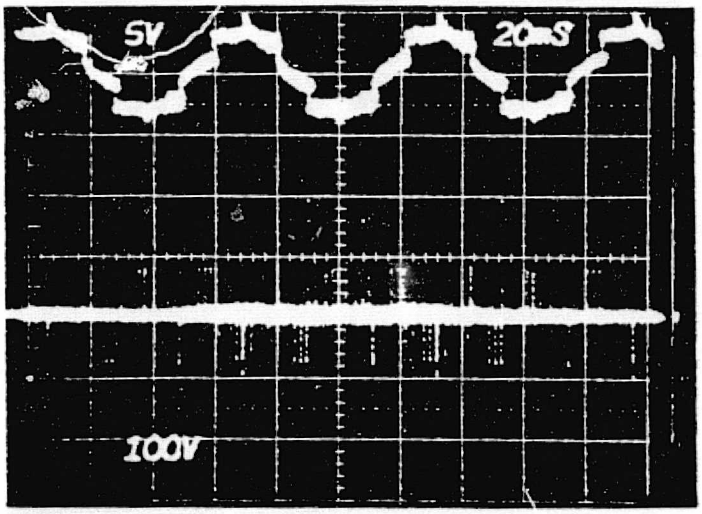
100 V/div V_{C1}



32

50 A/div I_B

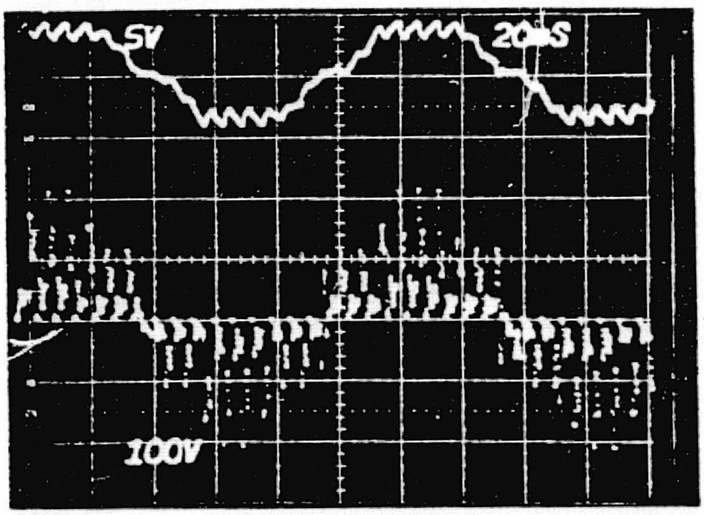
100 V/div V_{BN}



33

50 A/div I_B

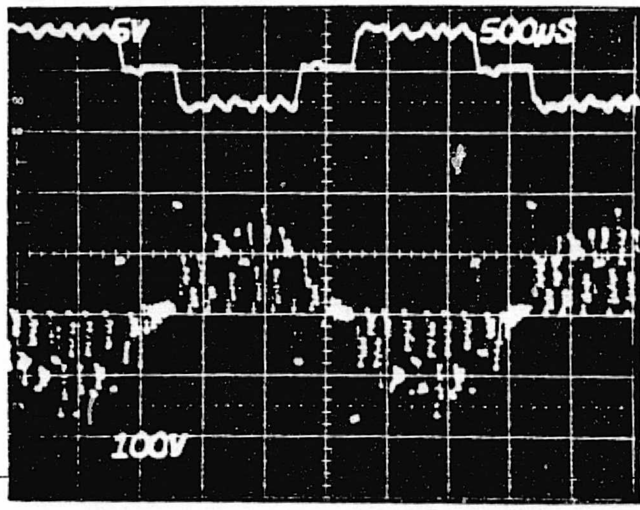
100 V/div V_{BN}



RUN 34

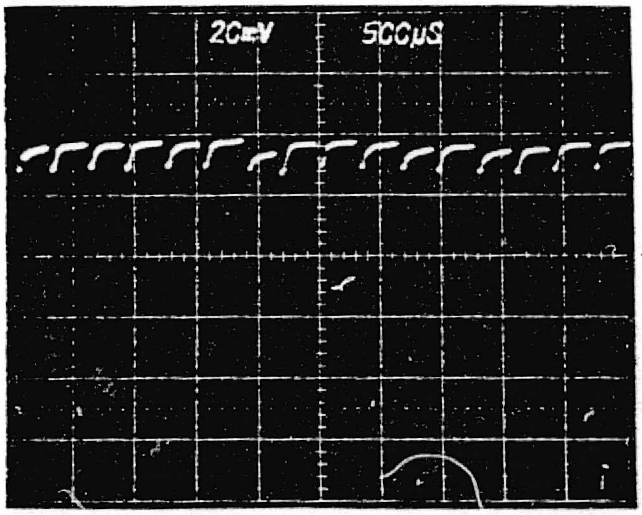
50 A/div I_B

100 V/div V_{BN}



35

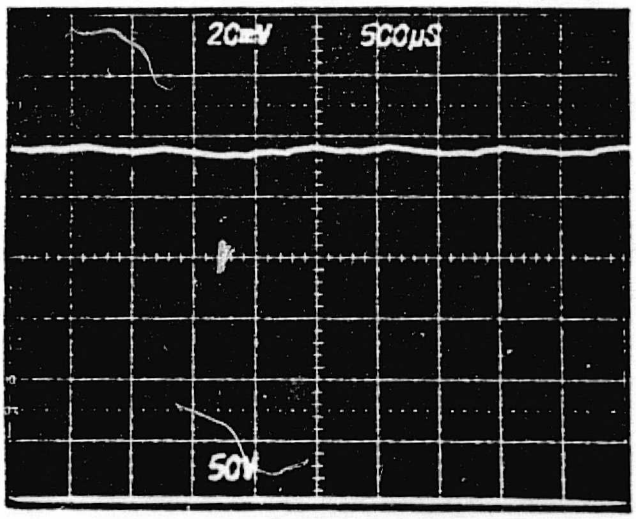
20 A/div I_M



36

20 A/div I_{QM}

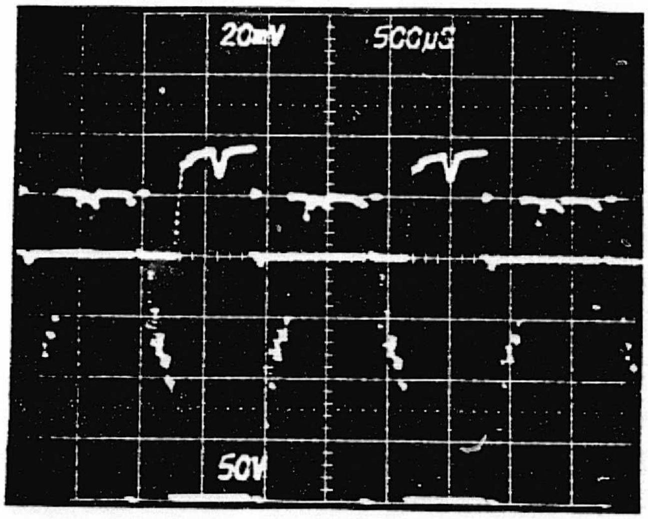
50 V/div V_{QM}



RUN 37

20 A/div I_{AN}

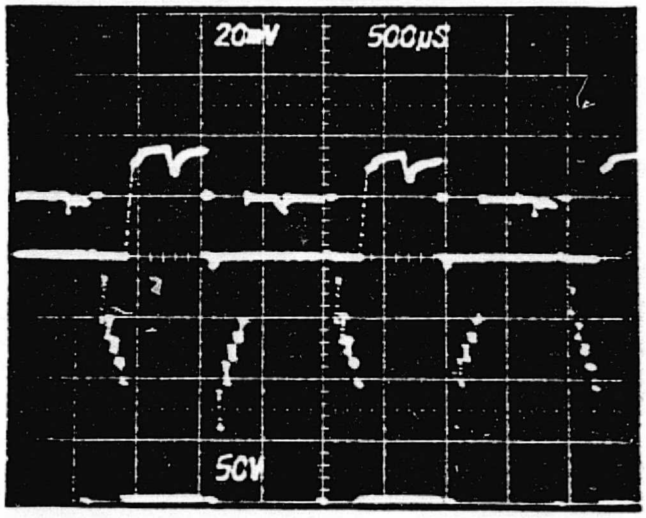
50 V/div V_{AN}



38

20 A/div I_{AP}

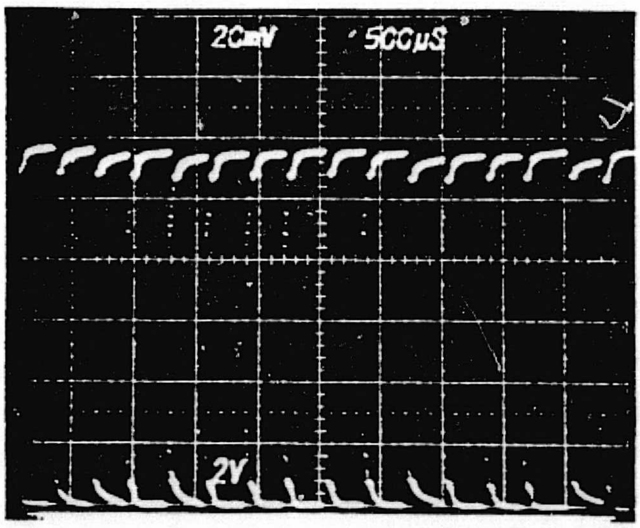
50 V/div V_{AP}



39

20 A/div I_M

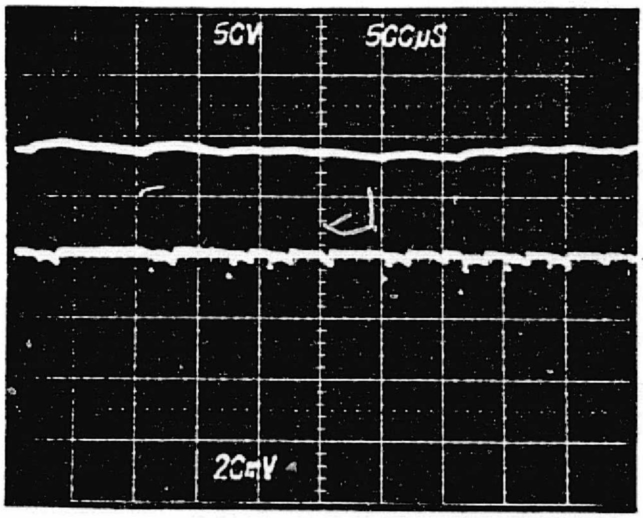
2 V/div I_8



RUN

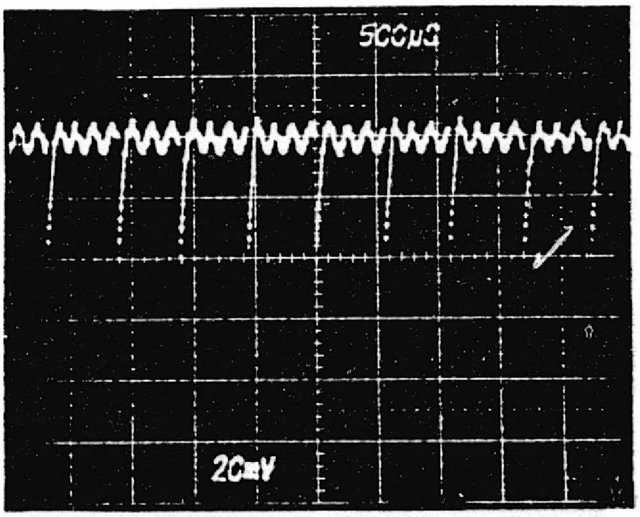
20 A/div I_L

50 V/div V_L



40

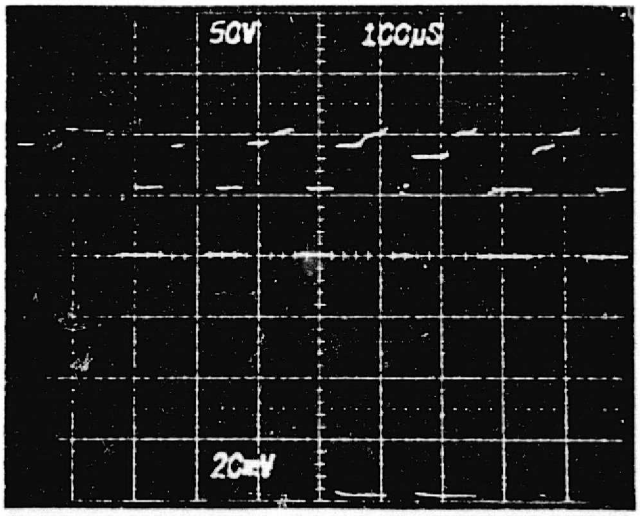
20 A/div I_M



41

20 A/div I_{QM}

50 V/div V_{QM}

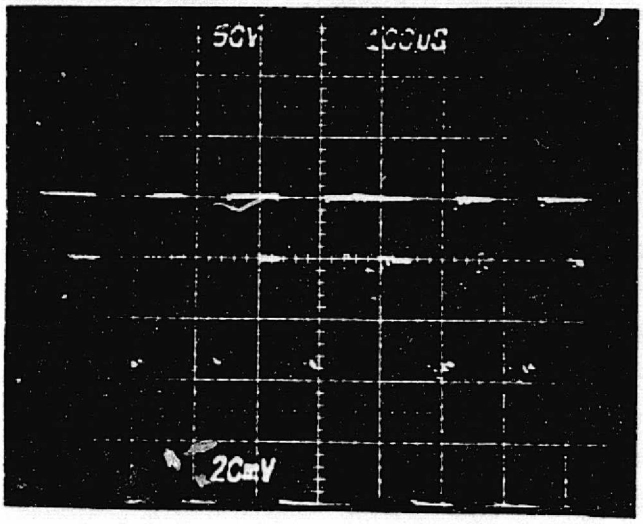


42

RUN 43

20 A/div I_{QB}

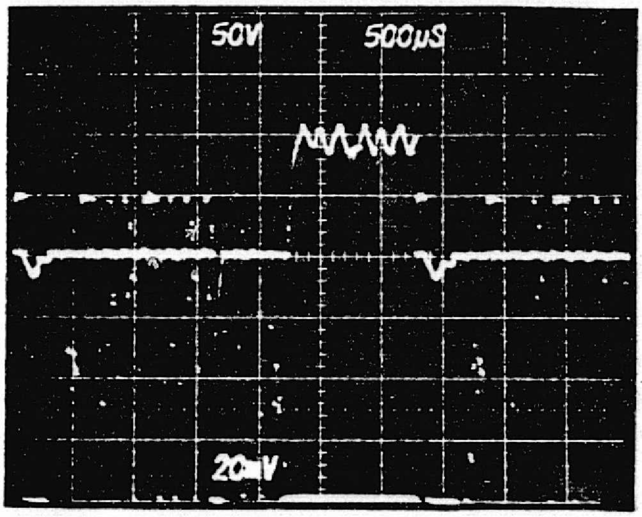
50 V/div V_{QB}



44

20 A/div I_{AN}

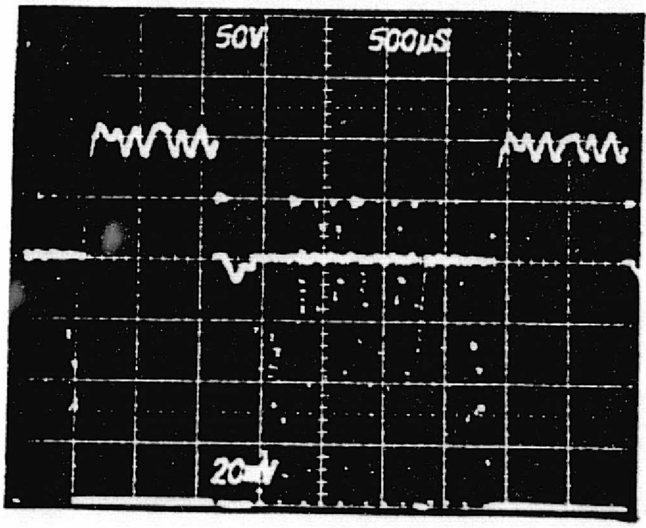
50 V/div V_{AN}



45

20 A/div I_{AP}

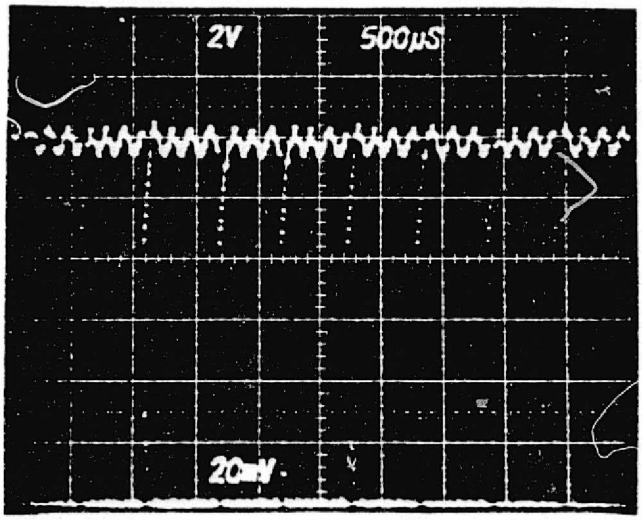
50 V/div V_{AP}



RUN 46

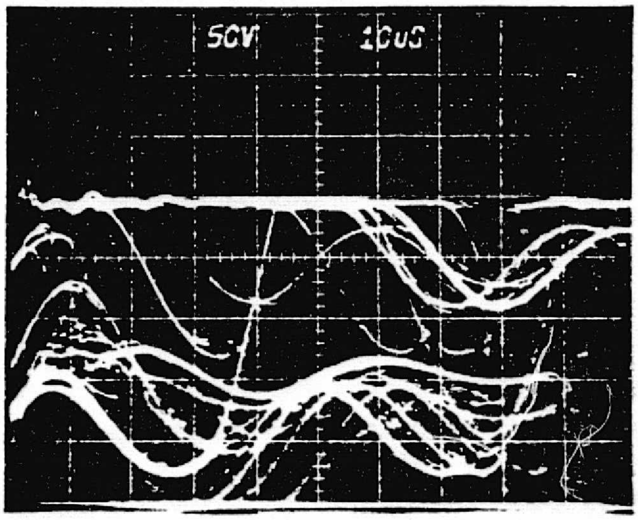
20 A/div I_M

20 A/div I_8



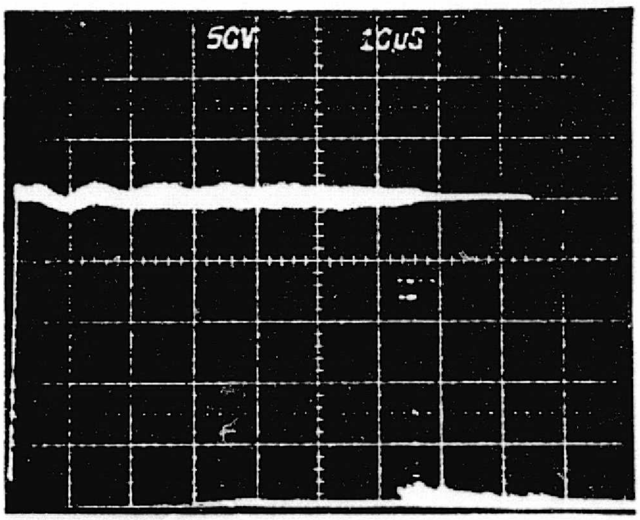
47

50 V/div V_{AN}



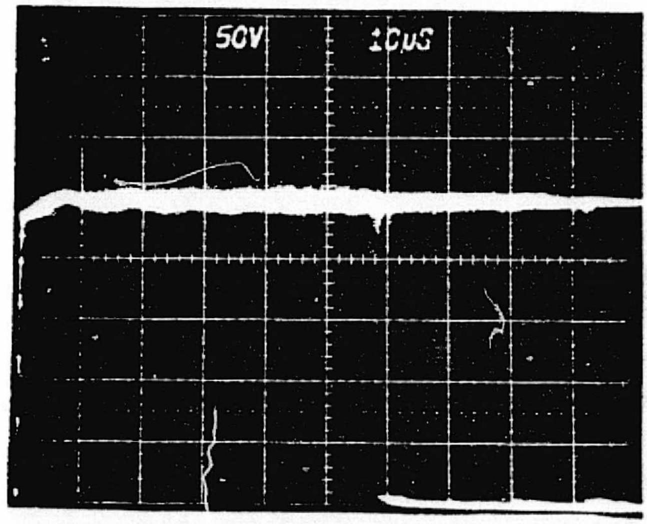
48

50 V/div V_{QM}



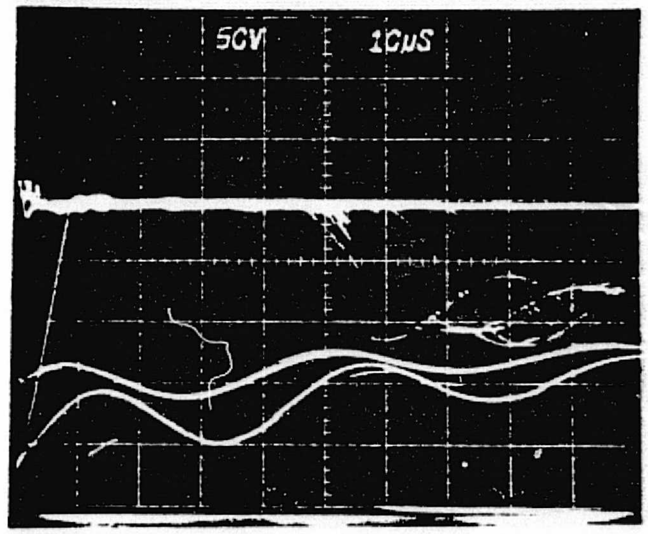
RUN
49

50 V/div V_{QB}



50

50 V/div V_{AN}



APPENDIX I

DESIGN VERIFICATION TEST PLAN

This appendix contains the design verification test plan presented in Delco document EE-22P-EMA-018.

Delco Electronics	General Motors Corporation Santa Barbara Operations 6767 Hollister Avenue Goleta, California 93017	EE- 22P-EMA-018		REV
		ENGINEERING EXHIBIT		
TITLE:	DESIGN VERIFICATION TEST PLAN FOR ELECTROMECHANICAL ACTUATOR	BY: A. H. Barrett/H. Hansen	SHEET 1 OF	
		APPROVED:	DATE:	

Submitted to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

In Accordance with
CONTRACT NO. NAS 9-14952

(DRL Item No. 4)

SECTION I

INTRODUCTION

This design verification test (DVT) plan outlines the tests to be conducted to confirm the design of the four-channel, deliverable electromechanical actuator (EMA). The tests which are to be conducted are summarized in Table 1. The paragraph references listed in Table 1 are those of the NASA Statement of Work. Table 1 indicates the number of active channels to be used in each test, the variables to be recorded on a strip-chart recorder, other types of data readout, the signal source to be used for each test, the load spring condition, and also shows whether the EMA output shaft is locked or free to rotate during the test.

The DVT will be conducted in the Delco EMA laboratory under the direction of an engineer who is thoroughly familiar with the EMA. If these tests are repeated at another facility, the operator and test director should be fully familiar with the EMA Operations Manual, and experienced in testing high-performance servo systems. The tests to be conducted are all straightforward, and can be conducted in any convenient sequence. However, it may prove to be more efficient to conduct all those tests which are done with load springs connected, then all those tests which are conducted with load springs disconnected, and finally all those tests which are done with the EMA output shaft locked.

TEST EQUIPMENT REQUIREMENTS

In conducting the DVT, the following equipment (or equivalent) will be required:

TEST	Active Channels	STRIP CHART RECORDER CHANNEL 1	2	3	4	DVM OR OTHER READOUT	SIGNAL SOURCE	SPRING ON	EMA LOCKED
3.3.4.1 Output Stroke	All pairs	Input Command	Output Position			Visible Mark on EMA shaft	* FRA BIAS	No	no
3.3.4.2 Output Velocity	All pairs	Input command	Output position	Tachometer channel 1	Tachometer channel 2	Strip Chart	FRA Square-wave	no	no
3.3.4.3 Output Torque	Any pair	Input command	Output position	Tachometer channel 1	Tachometer channel 2	Temperature read-out	FRA bias and sine-wave	yes	no
3.3.4.4 Displacement Linearity	Any Pair					DVM readout	FRA bias	no	no
3.3.4.5 Threshold	All pairs	Input command	Output position				FRA sine-wave	no	no
3.3.4.6 Position Null	All pairs					DVM readout	None	no	no
3.3.4.7 Hysteresis	Any pair					Oscilloscope and low-pass filters	FRA sinewave	no	no
3.3.4.8 Velocity Tracking	All pairs	Input command	Velocity error signal	Tachometer channel 1	Tachometer channel 2		Function generator triangular	no	no

* FRA: Frequency Response Analyzer.

TABLE 1 DVT SUMMARY

TEST	Active Channels	STRIP CHART RECORDER CHANNEL 1	2	3	4	DVM OR OTHER READOUT	SIGNAL SOURCE	SPRING ON	EMA
3.3.4.9 Frequency Response	Any pair	Input command	Output position	Position error	Tachometer output	FRA readout	FRA	no	no
3.3.4.10 Step Response	All pairs	Input command	Output position	Current command	Tachometer output		FRA Square-wave	both	no
3.3.4.11 Brake	One	Tachometer channel A	Tachometer channel B	Tachometer channel C	Tachometer channel D		FRA bias	no	yes
3.3.4.12 Chatter and Instability	All pairs						None	no	no
3.3.4.13 Velocity Gain Test	Any channel					DVM readout	FRA bias	no	yes
3.3.4.14 Torque Gain Test	Any channel					DVM readout	FRA bias	no	yes

TABLE 1. DVT SUMMARY (Continued)

HP 7404A Four Channel Strip-Chart Recorder
Weston 1410 Frequency Response Analyzer
Tektronix 7603 Four Trace Oscilloscope
Fluke 8040A Digital Voltmeter
Fluke 8600A Digital Multimeter
Lebow 1228-2K Torque Transducer
Gould SC1105 Bridge Amplifier
Precision Digital 701FJ Temperature Readout
Wavetek III Function Generator
HP 350D Attenuator Set

For convenience in understanding the design verification tests, relevant portions of the NASA Statement of Work have been placed in Appendix I of this DVT plan.

SECTION II

DESIGN VERIFICATION TESTS

OUTPUT STROKE (3.3.4.1)

PURPOSE

The purpose of this test is to demonstrate that the output load arm stroke is greater than ± 9 degrees but less than ± 11 degrees.

TEST PLAN

All pairs of EMA channels shall be operated, one pair at a time, with servo loops closed and the load springs disconnected. Using the Frequency Response Analyzer (FRA) bias control as the input command signal source for the EMA, and using a reference mark on the EMA output shaft, count the number of shaft rotations achieved as the input command is slowly varied from null to full EMA output in one direction. Record this value, and repeat for a command in the opposite direction.

DISCUSSION

Since the planetary gear reducer has a gear ratio of 238.71: 1, the EMA output shaft should rotate a minimum of:

$$9 \times 238.71/360 = 6.0 \text{ revolutions}$$

from null in either direction, and a maximum of:

$$11 \times 238.71/360 = 7.3 \text{ revolutions}$$

if the output stroke is to meet the EMA design goals.

TEST DURATION

All six combinations of channels can be tested for output stroke in less than one hour.

OUTPUT VELOCITY (3.3.4.2)

PURPOSE

The purpose of this test is to determine the maximum output velocity of the EMA.

TEST PLAN

The maximum output velocity of the EMA shall be determined by operating the system with a squarewave input command having an amplitude large enough to cause velocity limiting. All pairs of EMA channels shall be operated, one pair at a time, with servo loops closed and the load spring disconnected. The Frequency Response Analyzer shall be used to provide a squarewave command with an amplitude of $\pm$ 3 degrees at 0.5 Hz. The input command and output position shall be recorded on a strip-chart recorder. The EMA load velocity shall be determined by measuring the slope of the output waveform during the slewing interval.

DISCUSSION

The maximum load velocity of the EMA is dependent on the battery voltage. Since the nominal motor speed at 270V is 9000 rpm, and the overall gear ratio from motor to EMA load output is 2685.5 : 1, the typical EMA load output velocity is:

$$9000/2685.5 = 3.35 \text{ rev/min.}$$

or

$$3.35 \times 360/60 = 20 \text{ deg/sec}$$

TEST DURATION

All six combinations of channels can be tested for output velocity in less than an hour.

OUTPUT TORQUE (3.3.4.3)

PURPOSE

The purpose of this test is to demonstrate that the EMA can operate satisfactorily under three specified test conditions.

TEST PLAN

Any two channels may be selected for use in this test. The tests shall be conducted with servo loops closed and with load springs connected. The Frequency Response Analyzer (FRA) shall be used to provide the input command. A strip-chart recorder shall be used to record the input command, output position, and the tachometer signals from the two active channels. Thermocouples shall be placed on the housings of the two active motors (on the middle of the housing, opposite the cooling air inlet) and on the heat sinks of the active electronics channels (close to the motoring chopper switches). The thermocouples shall be connected to the temperature readout instrument.

CONDITION I: Adjust the FRA bias control to obtain an 8 degree output deflection on the load stand. Set the FRA for a 2.5 Hz sine wave, and adjust the amplitude to obtain a 1 degree peak-to-peak load motion. Operate for 26 minutes. Record the motor housing temperatures and temperatures of the electronics heat sinks at 1 minute intervals.

CONDITION II: Adjust the FRA bias control to obtain a 6 degree deflection of the load. Set the FRA for a 1.0 Hz sinewave with 4 degree peak-to-peak motion. Operate for 5.5 minutes, recording the temperature readings at 0.5 minute intervals.

DISCUSSION

The motor housing temperature rise is not expected to be more than 40°C during these tests. The temperature rise of the electronics heat sinks is not expected to be greater than 30° C.

DISPLACEMENT LINEARITY (3.3.4.4)

PURPOSE

The purpose of this test is to show that the displacement linearily, defined as the relationship between the input position command signal and the output position as measured by the output position transducer, in linear within $\pm$ 1% of full travel (FT).

TEST PLAN

This test shall be conducted with servo loops closed and load springs disconnected. Any pair of channels may be selected as active during the test. Use the Frequency Response Analyzer bias to provide an input command. Using a mark on the EMA shaft as a reference, rotate the EMA output shaft in one revolution increments from null to full travel in one direction. At each revolution, record the input command voltage and each of the four EMA output position transducer outputs (at A22-7) using a digital voltmeter. Repeat the measurements for commands in the opposite direction.

DISCUSSION

Since the gear ratio between the EMA and load is 238.71 : 1, one revolution of the EMA output shaft corresponds to 1.51 degrees of load motion. Since the command input limiter allows $\pm$ 10 degrees of travel, the nominal EMA output travel will be approximately:

$$\pm 10 \times 238.71/360 = \pm 6.6 \text{ revolutions}$$

As a simple method of demonstrating the linearity of the system, place a straight line through the data points taken at $\pm$ 6 revolutions, and calculate the deviations of all other data points from the straight line. The measured deviations should be significantly less than 1% of full travel for each output position transducer.

DISPLACEMENT LINEARITY (3.3.4.4) continued..

TEST DURATION

The data from this test can be taken in about an hour. Data reduction and linearity calculations will take about eight hours.

THRESHOLD (3.3.4.5)

PURPOSE

The purpose of this test is to demonstrate that the system threshold, defined as the largest sinusoidal input amplitude that may be applied at 0.01 Hz without producing output motion, is less than 0.05% of the input signal required to achieve full travel.

TEST PLAN

This test shall be conducted on all pairs of EMA channels, one pair at a time, with servo loops closed and load springs disconnected. The Frequency Response Analyzer shall be used to provide a 0.01 Hz sinusoidal input command with an amplitude of 0.0275 degrees. The input command and output motion shall be recorded on a strip-chart recorder. Since the recorder must be set at a high sensitivity to record these signals, if noise is excessive, 0.1 Hz single lag, low pass filters may be used to filter the signals which are being recorded. Output motion shall clearly follow the input command, demonstrating that the threshold design goal has been achieved.

DISCUSSION

The feedback transducers and their associated gearing are designed to allow full load travel of 55 degrees. Therefore, the system should respond to a low-frequency command amplitude of:

$$55 \times 0.05/100 = 0.0275 \text{ degrees}$$

in order to meet the design goal for threshold.

TEST DURATION

All six combinations of channels can be tested for threshold performance in about one hour.

POSITION NULL AND OFFSET (3.3.4.6)

PURPOSE

The purpose of this test is to demonstrate that with the input command signal at zero, and with the position offset controls set at zero, the output position of the EMA measured from its neutral position does not exceed 0.5% of full travel. The test is also to demonstrate that the position offset controls provide at least ± 5% of full travel from the neutral position.

TEST PLAN

This test is to be conducted on all pairs of channels, one pair at a time, with all servo loops closed and load springs disconnected. Null the position offset controls by placing a digital voltmeter from the wiper of the potentiometer to signal ground and using the screwdriver adjustment to achieve minimum voltage. With zero input command, measure the output load position for each pair of active channels. No null position offset greater than ± 0.275 degree should be obtained if the design goal position null accuracy is to be met.

With all position offset controls set fully counterclockwise, measure the output load position for each pair of channels. The resulting offsets should all be in the same direction and should be at least 2.75 degrees but less than 3.25 degrees. Repeat with all position offset controls set fully clockwise. The resulting offsets should be in the opposite direction from that found in the preceding test, and should be at least 2.75 degrees but less than 3.25 degrees.

DISCUSSION

The 0.5% position null requirement corresponds to an output of

$$(55 \text{ degrees})(0.005) = 0.275 \text{ degree}$$

The ± 5% position offset adjustment results in:

$$(55 \text{ degrees})(\pm 0.05) = \pm 2.75 \text{ degrees}$$

The offset range has therefore been designed to be 3 ± 0.25 degrees.

POSITION NULL AND OFFSET (3.3.4.6) continued

TEST DURATION

The position null and offset tests can be conducted in about one hour.

HYSTERESIS (3.3.4.7)

PURPOSE

The purpose of this test is to demonstrate that hysteresis of the EMA, defined as the maximum difference between output positions obtained when traveling clockwise then counterclockwise in response to a 0.01 Hz sinusoidal input, does not exceed 0.05% of full travel.

TEST PLAN

Any pair of channels may be selected for this test. The servo loops shall be closed and the load springs disconnected. The input signal shall be provided by the Frequency Response Analyzer (FRA). The input and output signals shall be filtered using a single lag, low pass filter having a break frequency of approximately 0.1 Hz. The filtered input signal shall be displayed on the x-axis of an oscilloscope, and the filtered output signal shall be displayed on the y-axis. With the FRA set to provide a sinewave at 0.01 Hz, the input signal shall be adjusted to give a command of approximately 0.1 degree peak-to-peak. The resulting oscilloscope display shall be photographed to provide a test record. To satisfy the hysteresis design goal, the measured hysteresis should not exceed 0.0275 degree.

DISCUSSION

The filters are used to minimize extraneous noise. The measured hysteresis should not exceed 0.05% of full travel, which corresponds to (55 degrees)(0.0005) = 0.275 degree.

TEST DURATION

This test can be completed in about one hour if all required filters and instrumentation are available.

VELOCITY TRACKING (3.3.4.8)

PURPOSE

The purpose of this test is to demonstrate that the steady-state angular velocity difference between any combination of two active motors does not exceed 3% of the maximum motor velocity for command signals within the normal operating range of the EMA.

TEST PLAN

This test shall be conducted on all pairs of channels with servo loops closed and load springs disconnected. The input command shall be a triangular waveform of ± 10 degree amplitude at 0.43 Hz so that the steady-state velocity shall be ± 17.2 degrees/second. The input command, velocity error signal and the tachometer output waveforms of the two active channels shall be recorded on a strip-chart recorder. The steady-state velocity error shall be less than 0.7 degree/second if the design goal for velocity tracking is to be met.

DISCUSSION

The maximum output velocity of the actuator is typically 23 degrees/second. The steady-state ramp velocity for this test is thus about 75% of maximum output velocity. To satisfy the 3% tracking velocity requirement, the steady-state velocity error should not exceed

$$(23 \text{ degrees/second})\ (0.03) = 0.7 \text{ degrees/seconds}$$

The velocity error signal undergoes a major transient when the command waveform changes from motion in one direction to the opposite. The velocity tracking error is therefore measured just before the command changes direction.

TEST DURATION

All six combinations of channels can be tested for cross-channel velocity tracking in about one hour.

FREQUENCY RESPONSE (3.3.4.9)

PURPOSE

The purpose of this test is to demonstrate that all combinations of two channels of the EMA meet the frequency response requirements of Figure 2 of the NASA Statement of Work.

TEST PLAN

This test shall be conducted on all six combinations of two channels of the EMA. The servo loops shall be closed and the load springs disconnected for this test. The Frequency Response Analyzer shall be used to provide the test signal and to read out the magnitudes of the input and output signals and the phase angle of the output with respect to the input. The input command shall be displayed on the strip-chart recorder along with output position, position error and tachometer output signals. The test frequencies shall cover the range from 0.1 to 20 Hz, and the signal amplitude should not cause significant velocity or torque limiting.

DISCUSSION

Since the EMA motor currents are limited to 40A and the motors have a maximum speed of about 9000 rpm, torque and velocity limiting can easily occur if the input signal amplitude is too large. The position output and velocity waveforms should therefore be checked at each test frequency to make sure that the EMA is operating in a linear manner during this test.

TEST DURATION

All six combinations can be tested for frequency response characteristics in eight hours.

STEP RESPONSE (3.3.4.10)

PURPOSE

The purpose of this test is to determine the step response characteristics of all pairs of EMA channels. Step commands of 2, 3, 4 and 5% of full travel are to be applied.

TEST PLAN

All six combinations of two active channels shall be tested. All servo loops shall be closed during the test and the step response characteristics shall be measured with and without load springs connected. A strip-chart recorder shall be used to record the input command, output motion, current command and tachometer signals. The Frequency Response Analyzer shall be used to provide a squarewave input command. The input signal shall be set successively for 1.10, 1.65, 2.2 and 2.75 degree steps, corresponding to 2, 3, 4 and 5% of full travel (55 degrees). The squarewave frequency shall be low enough to allow the transient to settle out before the next step occurs.

DISCUSSION

After recording the step response data, the step responses can be compared with the design goal envelope shown in Figure 3 of the NASA Statement of Work.

TEST DURATION

The step response measurements (including spring connect/disconnect) can be made in about four hours.

MOTOR BRAKE (3.3.4.11)

PURPOSE

The purpose of this test is to demonstrate that with three motors braked (i.e. in Standby mode) and the EMA shaft locked, full torque (in either direction) can be applied by the fourth motor without causing brake slippage. The test is to be conducted with each motor in turn acting as the driving unit.

TEST PLAN

Lock the EMA shaft (using the test fixture supplied for this purpose). With channels B, C and D in the Standby mode, use the Frequency Response Analyzer bias control to supply an input command which will cause full torque to be developed in channel A. Record all four tachometer signals on the strip-chart recorder. If slippage occurs, the tachometer signals will indicate the slip velocity. Repeat with full torque in the opposite direction. Repeat the sequence with channels B, C and D serving (in turn) as the active channel.

DISCUSSION

Since the brake disc is splined to the motor shaft, a slight motion of the motor rotor can occur within the backlash region, even though the brake is stationary. However, any continuous slippage should be clearly evident from the recorded tachometer signals.

TEST DURATION

The motor brakes can be tested in about two hours.

CHATTER AND INSTABILITY (3.3.4.12)

PURPOSE

The purpose of this test is to show that the EMA operates smoothly and without instability, excessive chatter, or excessive noise. Limit cycling under no load and steady state command conditions should not exceed 0.055 degrees peak-to-peak.

TEST PLAN

During all of the Design Verification Tests the EMA output shall be monitored to note any chatter, instability or limit cycles of an amplitude approaching 0.055 degrees peak-to-peak at the load (or 13 degrees peak-to-peak at the EMA output shaft). If anomalies are observed, the operating conditions shall be noted and the output motion shall be recorded on a strip-chart recorder.

DISCUSSION

Since the gear ratio of the planetary gear reducer between the EMA output and load is 238.71:1, the design goal for limit cycle amplitude of 0.055 degrees peak-to-peak corresponds to an EMA output shaft motion of

$$(0.055)(238.71) = 13 \text{ degrees peak-to-peak}$$

TEST DURATION

The EMA shall be monitored for chatter and instability throughout all of the Design Verification Tests.

VELOCITY GAIN TEST (3.3.4.13)

PURPOSE

The purpose of this test is to determine the open-position-loop velocity gain characteristics of the EMA.

TEST PLAN

This test may be conducted on any EMA channel, with the other three channels in Standby mode. The EMA output shaft shall be locked (using the fixture provided for that purpose). The position loop shall be opened by removing the resistor located at D3-6/11. Disconnect the tachometer leads on the channel under test. Ground D-J1-16 and apply a simulated tachometer signal at D-J1-15, using the Frequency Response Analyzer bias signal for this purpose. Use the velocity command test signal to bias the current command to full output. Vary the simulated tachometer signal to cause the motor current to change from full current (approximately 40 amps) to a low value (approximately 5 amps), taking readings of the tachometer signal and the motoring current at intervals of approximately 5 amps.

DISCUSSION

Over the range from 5A to 35A, the motor current should be an approximately linear function of the simulated tachometer signal. The tachometer scaling is 7 V/1000 rpm. With normal gains, the velocity gain should be approximately 0.035 A/rpm. During this test the velocity command should be of a polarity which causes the EMA to operate in a motoring mode. This can be determined by seeing that the output at D26-12 is in its low state (under 2 volts). If the system is in a plugging mode the current is limited to approximately 25 amps.

TEST DURATION

The velocity gain test can be done in about one hour.

TORQUE GAIN TEST (3.3.4.14)

PURPOSE

The purpose of this test is to determine the open-loop torque gain characteristics of the EMA.

TEST PLAN

This test may be conducted on any EMA channel, with the other three channels in the Standby mode. The EMA output shaft shall be locked (using the fixture provided for that purpose). The position feedback loop shall be opened by removing the resistor located at D1-3/14. Using the Frequency Response Analyzer bias control to provide an input command, vary the command to cause the motor current to vary from approximately 5 to 40 amps in 5 amp steps. Record the input position command and motor current at each step. The EMA output torque transducer output may also be recorded at each step.

DISCUSSION

Over the range from 5A to 35A, the motor current should be an approximately linear function of the position command, with a gain of approximately 450 Amp/degree. During this test the position command should be of the polarity which causes the EMA to operate in its motoring mode. If it is in the plugging mode, the current will be limited to approximately 25A. The EMA will operate in the motoring mode if the output at D26-12 is low (less than 2 volts).

Readings of output torque may be somewhat erratic if the motor is near its commutation position, if noise is present, or if a dither is created by backlash in the brake coupling. The nominal torque characteristic of the EMA motor is 2 in-lbs/Amp. Since the gear ratio between the motor and the EMA output shaft is 22.5:1, the EMA output torque gain has a nominal value of

$$(22.5)\ (2.0) = 45 \text{ in-lb/Amp}$$

TEST DURATION

The torque gain test can be run in about one hour.

APPENDIX I

RELEVANT PORTIONS OF

NASA

STATEMENT OF WORK

1.0 OBJECTIVES

The objectives of this Statement of Work (SOW) are as follows:

a. Conduct a thorough test and evaluation program of the redundant, four-channel, electromechanical actuator developed under NASA Contract NAS 9-14331.

b. Perform additional anaylsis and measurement tasks to resolve possible application problems.

c. Fully document the actuator design test and evaluation results and related analysis to be performed.

2.0 END ITEMS

The end items of this contractual effort shall be as follows:

a. EMA completed to a four-channel configuration, and associated hardware.

b. Test equipment and instrumentation residual from NAS 9-14331 or procured under the terms of this contractual effort.

c. Coded program tapes or computer card decks, listings, descriptions, and users instructions for those analytical models developed and used by the contractor under the terms of this contractual effort.

d. Documentation in accordance with the SOW and DRL (data requirements list).

3.0 TASK DESCRIPTION

The following defined tasks shall be completed under this SOW:

3.1 DESIGN, FABRICATION, AND MAINTENANCE

3.1.1 ELECTROMECHANICAL ACTUATOR (EMA)

The contractor shall perform those tasks necessary to complete the fabrication of the EMA to a full four-channel configuration in accordance with the current design base plus any modification(s) required to complete the design verification tests delineated herein under SOW paragraph 3.3. The current design base is represented by the latest design status achieved under NASA Contract NAS 9-14331. The contractor shall perform normal maintenance and repair of the EMA as necessary to enable the accomplishment of all SOW tasks, within the limitations of the NASA-furnished test stand, the EMA, and associated equipment, and to deliver it at the end of this contract.

3.1.2 TEST EQUIPMENT AND INSTRUMENTATION

The contractor shall perform all test equipment and instrumentation design and fabrication tasks as necessary to satisfy the test objectives of this SOW. The contractor shall maintain and repair all such equipment as necessary to complete the test objectives of this SOW.

3.1.3 NASA EMA TEST STAND

The contractor shall provide for modification to and maintenance and repair of the NASA furnished test stand as necessary to complete the test objectives of this SOW.

3.2 ANALYSIS

3.2.1 EMA ANALYTICAL MODEL DEVELOPMENT

The contractor shall perform those tasks necessary to develop analytical models of the EMA system and its simulated loads. Modeling shall include all major blocks such as the current source, power conditioner, motor, gearbox, tachometer, rotor position sensor, position sensor, and control electronics. System models shall be provided for analyzing steady state and transient conditions under various load conditions, linearized frequency response characteristics, and all major nonlinear effects such as hysteresis, torque limiting, and velocity limiting. The contractor shall establish the validity of the analytical models by establishing the correlation of analytical results with hardware test results (DVT, development, etc.) resolving any significant differences in steady state and/or transient performance.

The contractor shall utilize analytical results and hardware test results as necessary to optimize EMA systems gains and compensation to achieve the best possible system performance.

3.2.2 POWER SWITCH EVALUATION

The contractor shall analyze and evaluate the operating modes of all power components to establish their design margins. Actual measurements of the transient voltage and current profiles shall be made for all switch components in all operating modes. The compatibility of the electrical dynamics of the switch with the component ratings shall be explained. When inadequacies are found in the present designs, recommendations shall be made regarding methods to be used to provide safe operating regimes for all power components. Critical analysis and/or experiments shall be conducted where feasible, to verify that the proposed approach is adequate.

The contractor shall also provide an alternate design approach to the present power switching mechanization which would permit switch components to operate at low stress levels. A preliminary design and anaylsis of this approach shall be accomplished and documented.

The contractor shall submit a task plan for approval by the NASA technical monitor at least 30 days prior to start of this effort. The task plan shall be prepared to the requirements of DRL Item No. 3.

3.2.3 POWER ELECTRONICS BREADBOARD

The contractor shall perform the following work relative to the power electronics:

a. The contractor shall establish power switching requirements for the power components when driving the motor in each of 4 quadrants as required in figures 1, 2, and 3.

b. The contractor shall identify worst case operating conditions for the power component.

c. The contractor shall identify and specify minimum power component characteristics required for safe (reliable) operations under worst case conditions.

d. The contractor shall evaluate the characteristics of available power components (transistors, etc.) against required characteristics and established design margins and identify those cases where the ratings of presently available components are equal to or exceed said requirements and margins. The contractor shall evaluate components from two or more suppliers. The contractor shall evaluate the NASA-furnished power transistor (currently being developed by Westinghouse under the terms of Contract NAS 3-18916) and should consider the Power Tech Transistor PT-3523.

e. The contractor shall test the NASA-furnished power transistor and shall procure samples of power components with specifications adequate for the established requirments and design margins. The contractor shall test these components in circuitry which duplicates worst case conditions as determined in 3.2.3.b. The contractor shall establish power component design margins under these conditions. The contractor shall determine those power transistor parameters most critical to the identified switching requirements. The contractor shall recommend preferred power transistor parameters for each power switching application.

f. The contractor shall recommend a preferred power electronics design. The recommended design shall be submitted to the NASA technical monitor for review and approval. Power components determined to be most promising from 3.2.3.d and 3.2.3.e shall be incorporated in the recommended design.

The contractor shall fabricate the approved power electronics design. The contractor shall conduct tests of the power electronics against those design margins determined to be adequate in 3.2.3.e above. If, in the judgment of the contractor, it is not feasible to achieve adequate design and/or performance margins on the component and system levels, the contractor shall identify and analyze component and/or design inadequacies and recommend alternate components and/or design approaches that provide adequate design margins.

The contractor shall submit a task plan for approval of the NASA technical monitor at least 30 days prior to start of this effort. The task plan shall be prepared to the requirements of DRL Item No. 3.

The contractor shall submit a report on the evaluation, test and breadboard performance of the power components. The report shall be prepared to the requirements of DRL Item No. 4.

3.2.4 ANALYTICAL RESULTS

The contractor shall provide interim results of all analysis tasks to the NASA technical monitor on an informal basis. The contractor shall thoroughly document all analyses in a final report.

3.3 DESIGN VERIFICATION TEST

3.3.1 GENERAL

The contractor shall subject the EMA to design verification tests in accordance with this section to demonstrate compliance with this Statement of Work.

3.3.2 ELECTRICAL POWER

The contractor shall provide the electrical power for these tests at a nominal 270 vdc voltage level.

3.3.3 TEST EQUIPMENT

3.3.3.1 NASA EMA TEST STAND

The contractor shall utilize the NASA EMA test stand to load the EMA within the design limits of the test stand. The contractor shall measure the clevis arm displacement from the neutral (no load) position.

3.3.3.2 DELTA TEST EQUIPMENT AND INSTRUMENTATION

The contractor shall determine test equipment and instrumentation requirements in addition to that furnished from NAS 9-14331 which

are necessary to accomplish the test objectives of this SOW. Instrumentation shall include gearbox torque transducers. The contractor shall consider the need for position transducers to measure for load deflection, temperature sensors, and power measurement instrumentation. The contractor shall provide all acquisition and installation of additionally required test equipment and instrumentation.

3.3.4 PERFORMANCE TESTS

Many of the EMA performance requirements given in this section are expressed in terms of percentage levels based on 55 degrees full-stroke displacement of the output rotary actuator(s) for all combinations of two motors operating. The displacement levels are expressed in terms of % FT (full travel). Hereinafter, 100% FT shall represent the 55 degrees of full-stroke displacement.

The contractor shall evaluate all of the actuator performance or design specifications defined in the SOW for NAS 9-14331 as applicable against the design baseline established in section 3.1.1. As a minimum, the contractor shall test to or against all specifications identified in subsequent paragraphs of this section. It is recognized that this is a test program and that all specifications represent design goals only. Where specifications include "all combinations of any two channels," detailed test of any two channels substantiative as typical is acceptable.

3.3.4.1 OUTPUT STROKE

With any single or combination of any two channels operating, the EMA shall be capable of positioning the output over the entire stroke; i.e., 55 degrees (+15, -40 degrees).

3.3.4.2 OUTPUT VELOCITY

For all combinations of any two channels operating at no load, the EMA shall provide maximum open loop (open position loop only) velocity of 21 degrees/second. Minimum velocity requirements under loaded conditions are specified in figure 1.

3.3.4.3 OUTPUT TORQUE

The EMA, for all combinations of any two channels operating together in either direction of rotation, shall be capable of the dynamic response as specified in figure 1.

3.3.4.4 DISPLACEMENT LINEARITY

For all combinations of any two channels operating, displacement linearity, defined as the relationship between the input position command signal and the output position as measured by the output position transducer, shall be linear within 1% FT.

3.3.4.5 THRESHOLD

For all combinations of any two channels operating at no load, threshold, defined as the largest sinusoidal input amplitude that may be applied at 0.01 Hz without producing output motion, shall not exceed 0.05% FT of the input signal required to achieve 100% FT.

3.3.4.6 POSITION NULL

With the input signal at zero, for all combinations of any two channels operating at no load and the position offset controls set at zero, the output position of the EMA measured from its neutral position shall not exceed 0.5% FT. The position offset control of any channel shall be capable of displacing the neutral position of the output clevis an amount equivalent to $\pm 5\%$ FT.

3.3.4.7 HYSTERESIS

For all combinations of any two channels operating, hysteresis, defined as the maximum difference between output positions obtained when traveling clockwise then counterclockwise during a 0.01 Hz sinusoidal input with an amplitude of 50% FT, shall not exceed 0.05% FT.

3.3.4.8 CROSS-CHANNEL VELOCITY TRACKING

The steady-state angular velocity difference between any combination of motors operating shall not exceed 3% of maximum motor velocity, for any command signal within the operating range applied equally to all channels.

3.3.4.9 FREQUENCY RESPONSE

The EMA, for all combinations of two channels operating, shall be tested closed loop to demonstrate compliance with figure 2. The input amplitude shall theoretically give $\pm 0.5\%$ FT at 0.1 Hz. The amplitude ratio, output peak-to-peak displacement achieved divided by 1% FT, expressed in decibels and phase shift, expressed in degrees, shall fall within the envelope shown in figure 2.

3.3.4.10 STEP RESPONSE

Tests, for all combinations of two channels operating, shall be performed to demonstrate compliance with requirements of figure 3.

3.3.4.11 MOTOR BRAKE

Each brake shall brake a de-energized motor from full speed to zero speed while holding against that torque required to drive the maximum load. No electrical power shall be rquired to engage the brake (brake motor).

3.3.4.12 CHATTER AND INSTABILITY

The EMA shall operate smoothy without instability excessive chatter or excessive noise under all conditions specified herein. Limit cycling for any channel under no load and steady-state command conditions shall exceed 0.055 degrees peak-to-peak.

3.3.4.13 VELOCITY GAIN TEST

The contractor shall perform tests to determine no-load, open position-loop velocity gain characteristics for each channel separately and for all combinations of any two channels.

3.3.4.14 TORQUE GAIN TEST

The contractor shall perform tests to determine open-position-loop torque gain characteristics for each channel separately and for all combinations of any two channels.

3.3.5 TEST PLAN

The contractor shall submit a detailed test plan for approval by the NASA technical monitor at least 30 days prior to the start of testing. The test plan shall be prepared to the requirements of DRL item no. 5.

4.0 PROGRAM REQUIREMENTS

4.1 CONFERENCE REQUIREMENTS

The contractor shall support formal reviews. These reviews shall be chaired by NASA JSC, and the contractor shall prepare and make available to the attendees all documentation necessary to accomplish the objective of the review. One (1) review shall be conducted at the Johnson Space Center; two (2) reviews shall be conducted at the contractor's facility at Goleta, California.

4.2 DOCUMENTATION REQUIREMENTS

The contractor shall furnish all data items identified and described on the DRL (data requirements list), JSC Form 2323. The data items

shall be prepared in accordance with the DRD (data requirements description), NASA Form 9, and JSC Form 2341, attached to the DRL and referenced on the DRL for each line of data specified thereon. Where practical, the contractor's own internal documents shall be utilized to meet and/or supplement the requirements specified in the applicable DRD. Internal documents need not be retyped or reprinted prior to submission.

Attachment 1 is a completed DRL with associated DRD's applicable to this Statement of Work.

EM ACTUATOR DYNAMIC RESPONSE

REQUIREMENTS

CONDITION I	DR (%)	TIME (MIN)	RATE (DEG/SEC)	EM (IN-LB x 1[illegible])
STEADY STATE	-	-	10	.495 (1)
LIMIT CYCLE (2.5 (4) Hz @ 1° PP)	100	26	5 (Avg)	.300 (2)

CONDITION II				
STEADY STATE	-	-	15	.495 (3)
LIMIT CYCLE (1 Hz @ 4° PP)	100	5.5	8 (Avg)	.140 (Avg)

CONDITION III				
STEADY STATE	-	-	20	.357
LIMIT CYCLE	100	1.5	8 (Avg)	.140 (Avg)

CONDITION IV	100	5	0	.495

DESIGN GOALS:

(1) $.518 \times 10^6$ IN-LB

(2) $.455 \times 10^6$ IN-LB

(3) $.539 \times 10^6$ IN-LB

(4) .3 Hz @ 1° PP

FIGURE 1

ORIGINAL PAGE IS OF POOR QUALITY

EM ACTUATOR FREQUENCY RESPONSE
(AMPLITUDE RATIO)

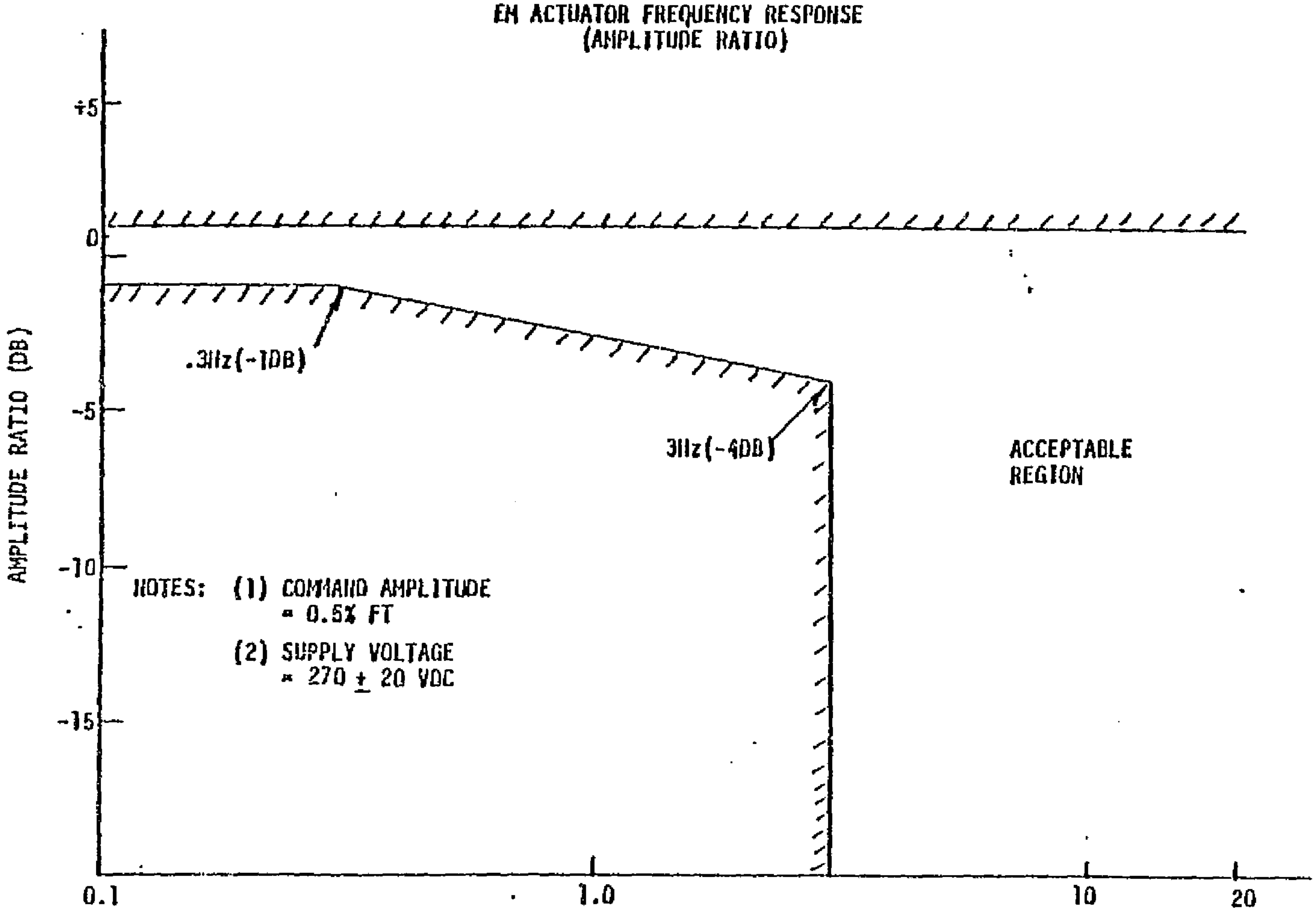


FIGURE 2

C-3

EH ACTUATOR FREQUENCY RESPONSE
(PHASE SHIFT)

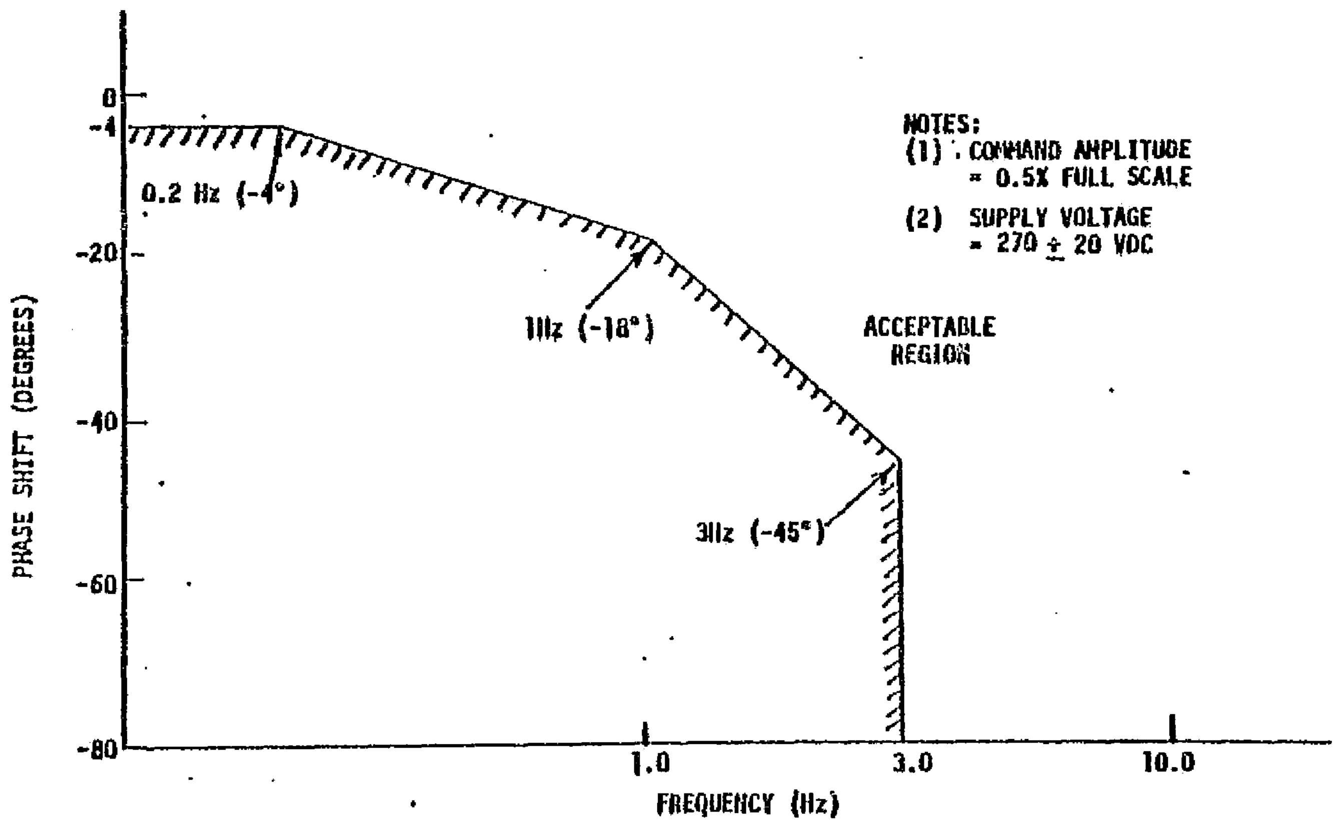


FIGURE 2a

ORIGINAL PAGE IS OF POOR QUALITY

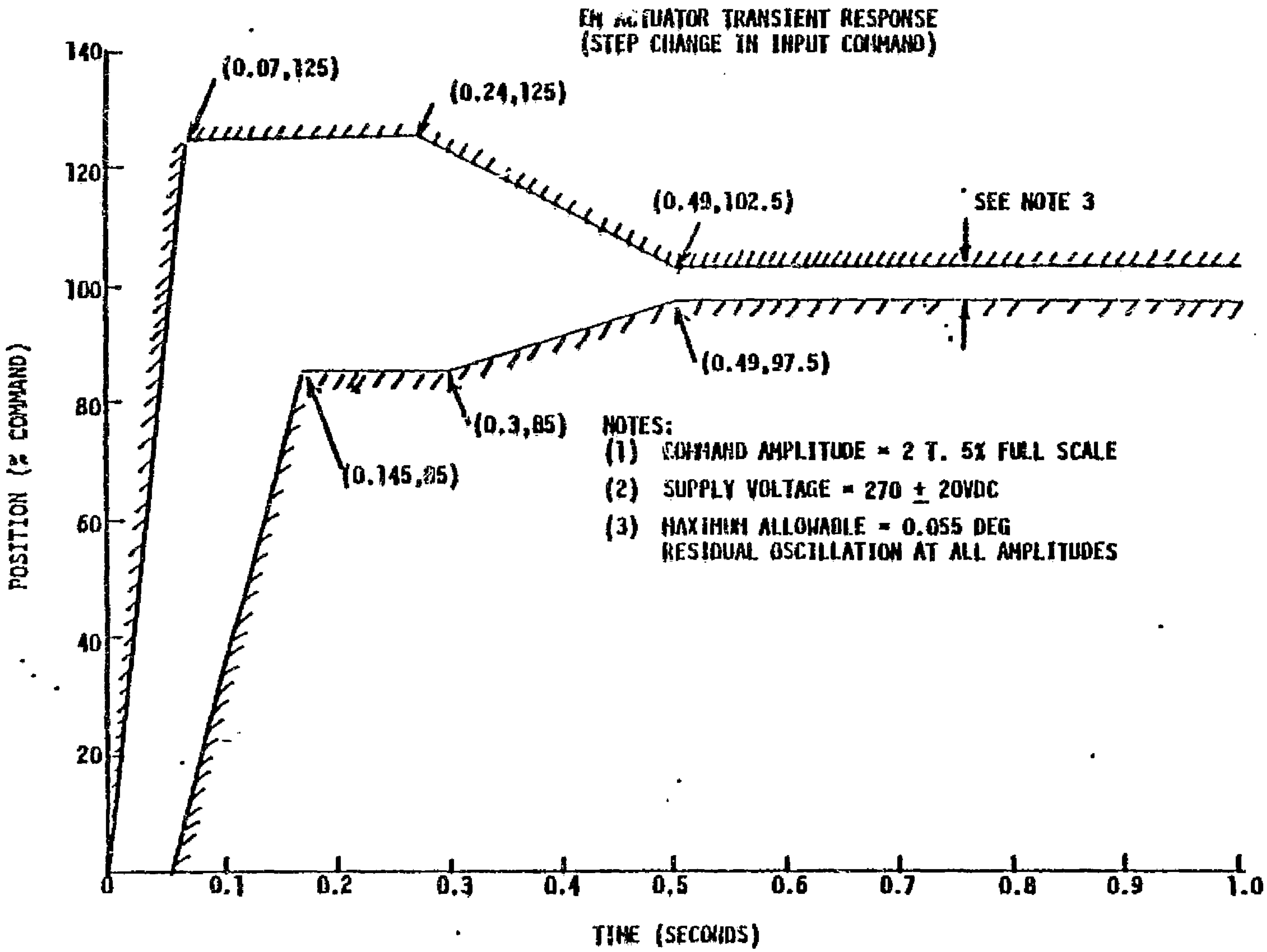

EM ACTUATOR TRANSIENT RESPONSE
(STEP CHANGE IN INPUT COMMAND)
140
120
100
80
60
40
20
0
(0.07,125)
(0.24,125)
(0.49,102.5)
SEE NOTE 3
(0.49,97.5)
(0.3,85)
(0.145,85)
POSITION (% COMMAND)
NOTES:
(1) COMMAND AMPLITUDE = 2 T. 5% FULL SCALE
(2) SUPPLY VOLTAGE = 270 ± 20VDC
(3) MAXIMUM ALLOWABLE = 0.055 DEG
RESIDUAL OSCILLATION AT ALL AMPLITUDES
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
TIME (SECONDS)

FIGURE 3